Eco- and Material-Efficient Utilization Applications of Biotechnologically Modified Fiber Sludge

Matti Kuokkanen,[a,]*Olli Mäentausta,[b] and Toivo Kuokkanen [c]

Wood fiber sludge is a by-product of the pulp and paper industry, and 750,000 tons are generated per year in Finland. When aqueous fiber sludge (solid matter content 10 to 20%) is modified with water and enzymes, it is called biotechnologically modified fiber sludge (BMFS). So far, native fiber sludge has been only a waste material in Finland, but according to a new waste law, its waste tax is 70 € per ton. According to the present EU and Finnish strategies on waste materials, circular economy, and material-efficiency, all waste must be utilized primarily as material (reuse, recycling) and secondarily as energy. For these reasons, it is very important to develop new eco-, cost- and material-efficient utilization methods for this aqueous “pure waste” instead of landfilling and combustion. Continuing earlier experiments, which proved that BMFS is a good and efficient binding agent for combustion pellets, BMFS was studied in new utilization applications such as bedding pellets for horses as well as a road and horse riding hall dust binding agent. In laboratory measurements and field experiments, BMFS is a very efficient dust-binding agent and effective binding agent for bedding pellets.

Keywords: Wood fiber sludge; Biotechnologically modified fiber sludge; Bedding pellet; Dust; Binding agent; Riding hall sand; Material-efficiency

Contact information: a: University of Oulu, Research Unit of Sustainable Chemistry, P.O. Box 3000, FI - 90014 Oulu, Finland; b: MFibrils Ltd, Pajutie 1 C 10, FI - 80110 Joensuu, Finland; c: University of Oulu, Centre for Environment and Energy CEE, P.O. Box 8300, FI - 90014 Oulu, Finland;
**Corresponding author: matti.kuokkanen@oulu.fi*

INTRODUCTION

According to the current EU and Finnish strategies on waste materials, all kinds of waste must be utilized primarily as material (reuse, recycling) and secondarily as energy. If neither of these utilization methods is possible, they should be disposed of by ecologically beneficial methods. The present goals of the Finnish waste strategy were given in the national waste plan approved by the Finnish Council of State on the 10th of April 2008 (Ministry of The Environment, Finland 2008) and in the new waste law, which took effect on the 1st of May 2012 (Ministry of The Environment, Finland 2011). Currently, material efficiency is an essential topic in promoting sustainable use of natural resources. The current waste hierarchy is presented in Fig. 1 (Sligo County Council 2012).

Thus, the goals of utilizing biomass as pellets, waste adhesive materials as binding agents in pellet production, and bio-pellet ash for different applications, all represent the top global goals of utilization of waste materials and industrial by-products.

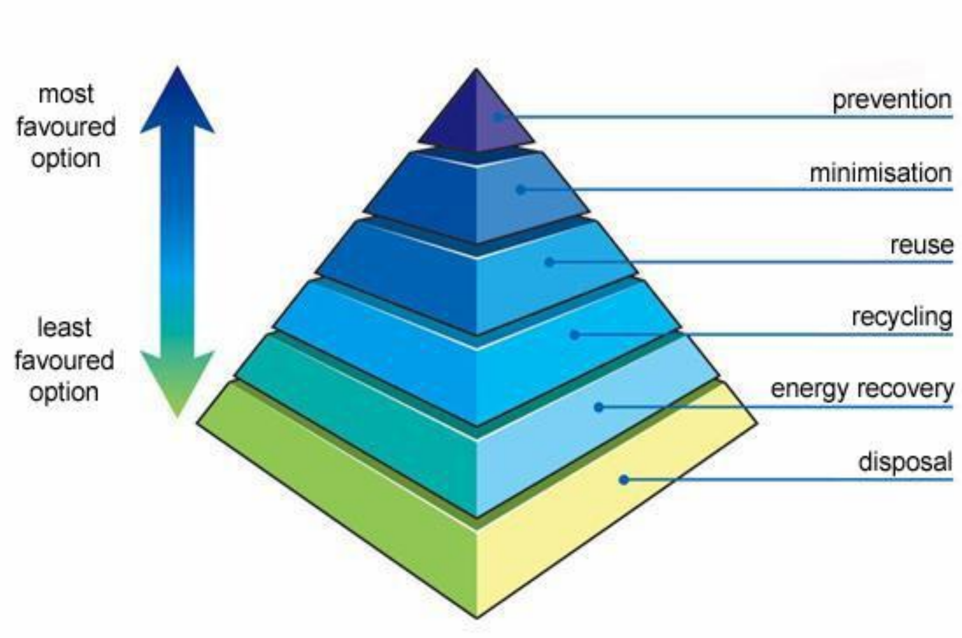

Fig. 1. Waste hierarchy (Sligo County Council 2012)

Wood fiber sludge (Fig. 2) is generated as a by-product of the pulp and paper industry. In Finland, 750,000 tons per year of wood fiber sludge are generated. In the past, fiber sludge was either incinerated or placed in landfills. However, the energy production and fuel usage of fiber sludge are not very efficient, and therefore new ways and research are being sought to utilize it. Wood fiber is low in nutrients, but includes plenty of slowly decomposing organic matter. Fiber sludge has so far been the only waste batch in the pulp and paper industry without waste tax costs, but according to a new waste law of industrial landfills in Finland (1126/2010), fiber sludge as well as bio ash is taxed at a rate of 70 € per ton since January 2016. This has tended to activate the development of new types of utilization of this "pure aqueous waste." These new innovative applications, several of which are currently associated with the production of pellet-based products, in particular biotechnologically modified fiber sludge, are becoming a valuable raw material for various kinds of organic products, in accordance with industrial ecology, green chemistry, and material efficiency, as well as the principles of the EU and Finland’s national waste strategy and circular economy.

Fig. 2. Native and biotechnologically modified wood fiber sludge

Background

Biotechnologically modified fiber sludge preparation is a biomechanical process, in which surface structures of pulp fiber sludge are decomposed and modified. Commercial available enzymes (cellulases, hemicellulases, laccases and lipases) were used as part in this biomechanical process. As a result of processing, a gel-like fiber mass is generated. In the gel-like physical state of cellulose, the fiber is broken into microfibrils. With this gel-like fiber mass, it is possible to cost-efficiently replace the fiber raw materials and recovery applications for industrial processes more easily than the original fiber waste mass. Free hydroxyl groups on the surface of the biotechnological fibers have a strong tendency to aggregate by hydrogen bonds, which join to form a larger fibril agglomerate, with its own cellulose fibers and those around. (Fig. 3.) This happens particularly in the drying of microfibrillized cellulose. Because of the versatile fiber construction characteristics (small size, large surface area, good binding capacity) fiber binding agent delivers the following advantages: 1) substantial energy savings in the drying (10 to 15%), 2) uniform quality rheological properties of the shredded material, which allows for the criticality of raw material variability to be reduced, 3) compensation of the material friction allows a higher production rate in pelletizing, 4) significantly expands the raw material base for the pellet production, 5) the pellet mechanical durability is improved more rapidly, thus reducing the pellet storage time, 6) reducing the amount of fines and thus prevent dusting of the pellet and energy loss, 7) slowing down pellet biodegradation substantially, 8) promotion of the implementation of the EU and Finnish national renewable energy, waste strategy and material efficiency targets, and circular economy, 9) in addition to the currently existing tree species utilized, the waste biomass is more cost-, material-, and eco-efficiently recycled, and 10) providing for the development of new applications such as bedding pellets.

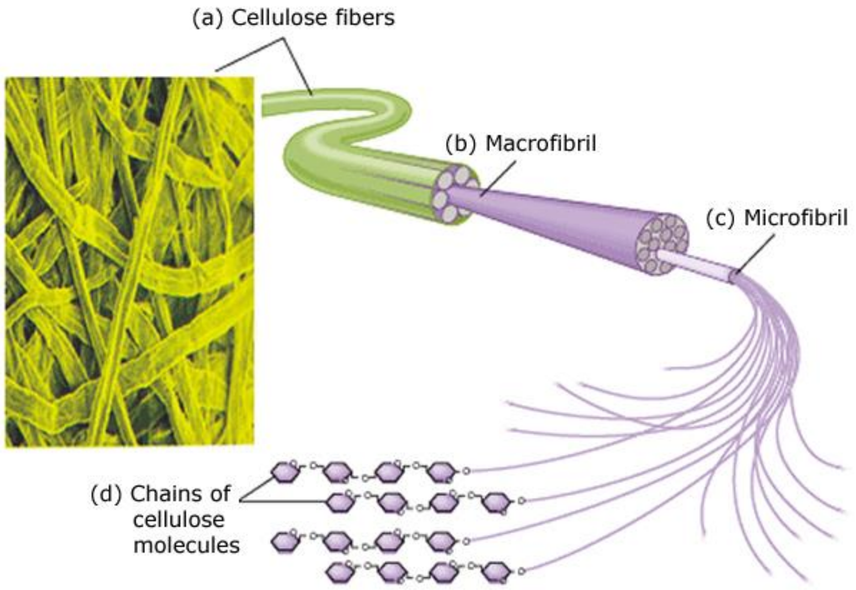

Fig. 3. Fibrillization of cellulose in the enzymatic treatment of fibers (Adam-Day 2016)

Road dust is fine particles in the air, arising mainly as a result of sanding roads and asphalt surface wear, as well as across the sand on the roads during dry time periods and is known to be harmful to health. Road dust is a problem, especially in high traffic cities where traffic keeps street dust in the air constantly. Fine particles cause health problems for all ages, and are particularly harmful to those suffering from respiratory diseases. Road dust can cause symptoms in almost the entire population, but the most likely to suffer from dust asthmatics are children and the elderly. The symptoms are familiar: itchy eyes and throat and coughing. For the most vulnerable, road dust causes respiratory symptoms. However, the health effects are difficult to study, because road dust is not the only pollution reducing the air quality. Road dust is often mixed with other air pollutants that impair air quality. In Finland, road dust presents a problem especially in the spring, when the streets are revealed from snow and ice and sand and gravel that were spread during winter time will dry and can raise dust. The worst street dust is caused by traffic. The problem comes to a head in the summer, because the spike tires hone the road surface quite effectively. As the result there is a fine-grained sand, and the dust in the air increases. Since the road dust pollution problems are encountered every spring, prevention of dust must be invested in much more in the future. The emergence of road dust can for example be prevented by increasing the high molecular dust binding and the water-binding agents, such as biotechnologically modified fiber sludge.

In Finland cleaning of road dust is studied all the time, and new ways are under development. For example, the city of Helsinki has already cleaned the streets with calcium chloride for a couple of years, or salt with a solution of common salt, where sodium is replaced with more expensive calcium. The results are clearly better than what is obtained if the streets are cleaned only with plain water. The street dust level is highest in the spring time, but the dust combating eco-friendly solutions are used as needed, even in summer.

In previously implemented Mfibrils Ltd's and EkoPelletti project experiments (Kuokkanen *et al.* 2012), for example in dust prevention by bedding pellets, the idea of using biotechnologically modified fiber sludge for dust suppression was created (Kuokkanen *et al.* 2014). Perhaps the most important practical application of fiber sludge in this application, for the reasons described above, can be considered the binding of road dust. Sand dust consists mainly of rock that is rich in silicate compounds. These silicate compounds have hydroxyl groups with which free hydroxyl groups of biotechnologically modified fiber sludge form hydrogen and other chemical bonds. Thus, the network between dust material and pulp fiber fractions is generated that contains larger particle clusters that do not cause dusting as easily as the mere small-sized sand particles. During this research the appropriate operating mode of fiber sludge solution (metering, mixing ratios, and shape) in different types of dust suppression applications has been developed. Preliminary results for this dust binding application have been very promising. The experiments have indicated that the use of a dust binding requires further development, for example the distribution and dissemination of the hardware structure of the dust-binding agent. However, it should be noted that the use of fiber sludge as a dust binding is a truly ecological solution compared to the use of the current dust-binding agents such as $CaCl_2$. Thus, this fiber sludge application can be regarded as a very important ecological potential for exploitation up to the global level, in which case it is a potential cleantech product that can be exported.

Horse riding is currently one of Finland's fastest growing sports hobbies. The horse business has been expanding globally for many years. In Finland there are approximately 80,000 horses and currently the most common litter material is peat (75%). The horse litter use amount in Finland is approximately 100,000 tons per year. As litter material, peat has features of a good odor binding and absorption, but also some negative aspects such as dusting and messiness. The availability of peat also depends on the weather conditions. Furthermore, there are also restrictions on the use of peat in such a way that no new peat bogs are to be opened, and the use of old ones is stopping. Heating of state institutions will no longer be done by oil and non-renewable resources such as peat (In Finland, contrary to the EU, peat is hitherto classified as a renewable natural resource). Therefore, straw pellets for those reasons have gained ground, but they are also associated with problems such as dusting, mold, allergies, odor, and poor/uneven quality, as well as the uncertainty of harvesting depending on the weather circumstances. Horses also have eaten straw pellets, which in turn has led to life-threatening colic. Of particular concern is the risk of the spread of diseases, for example, African swine fever (which spreads along the straw pellet raw material, and which is imported from an increasingly greater distance from the south, because the Finnish straw material is not sufficient as demand grows) has devastating consequences for the pig industry in Finland. The disease is not contagious for cows or horses, but they may be carriers of the disease. The disease severity is comparable to mad cow disease. All of these factors have contributed to the fact that it has been necessary to develop an equine industry product which meets the needs of users. The aim is to provide a product that combines the good properties of all products in litter market plus the missing features, *i.e.*, smell binding capacity of the peat, ease of use and time saving of the pellets, dustproofing, good absorbency, anti-bacterial properties, clumping, price-quality ratio, good natural fragrance, safe, does not cause allergies and colic, disease-free, and ecological. New bedding pellet has attracted interest internationally as a new innovation due to its characteristics, ecology, and versatility. Testers have been tens of equestrian professionals and vets. The first export country of bedding pellet has been Sweden (more than 360,000 horses, litter use amount approximately 500,000 tons).

Perhaps the most important practical problems of pelletizing are size retention, strength, and dust-related problems. If these problems could be eliminated, then the production of pellets could be simultaneously enhanced, increasing the amount of pellet production, improving the quality of the pellets and thus the economic viability of the sector. Furthermore, if used binders and additives are products remanufactured from industries, from the forest industry in particular, and are classified as by-products or waste, it is also a question of material- and eco-efficient utilization of waste. New binders and additives suitable for the pellet production are required to have certain properties in order for their use on an industrial scale pellet plant to be economically viable. The binding agent should be cheap, environmentally friendly, and easily accessible. Furthermore, the binding agent properties must be such that even a small amount of binding agent positively affects the quality of the pellets produced, and the binding agent causes no harmful emissions in pellet combustion or is not harmful to animals in bedding pellet use due to its small amount (e.g. in bedding pellets the solid matter content of sludge is only below 1 %). It should be also noted that even though the pelletized feedstock material must be located close to the pellet plant, because of the small percentage, the location of the binding agent source does not need to meet the same criteria.

Regarding quality and price of the final product, some desirable effects of binding agent usage are a positive effect on the calorific value (when it is a question of combustion of pellets), cohesion characteristics, dust prevention, and slowing biodegradation. There are also lubricating properties of the pellet machine matrices and other parts, which make it possible, for example, to increase the production rate or to regulate the processing of the raw material friction properties. The aim in the future is to expand the base of wood pellet raw material by utilising more low-value and/or moist biomass, especially logging residue from thinning. To improve the quality of pellets, commercial and industrial by-product materials are commonly used as binding agents in pellet production (Obernberger and Thek 2004; Thek and Obernberger 2004; Kaliyan and Vance 2009; Kuokkanen 2013). Also, considering the profitability of production and some occupational safety problems (wood dust exposure, fire and explosion risk, coherence, *etc.*), it is practical to use binding agents. By using some new binding materials, such as biotechnologically modified fiber sludge, it seems to be possible to prevent mechanical decomposition and pellet biodegradation, which can cause substantial economic losses in full-scale pellet production.

Regarding eco- and cost-efficient concerns, it is notable that even after drying the raw material and other pre-treatment methods and improving the quality with the binding agent usage, the total cost must be kept as low as possible, the production of pellets remains competitive and economically viable for the pellet producer. Also, the pure bio-ashes from the combustion of wood pellets provide a variety of valuable utilization applications, such as fertilizer use (for example the use of granulated various new applications bio ash based products) and are predicted to make a clear positive impact on the profitability of pellet production in the future (Kuokkanen 2013; Pesonen *et al.* 2016).

Up to 20 million tonnes of waste wood biomass per year are left unused in Finland, mainly in the forests during forestry operations, and the difference between annual growth and felling substantially exceeds the amount currently. Also, wood pellet-based products other than the combustion recovery options, such as the use of animal litter and dust suppression, are currently almost without examination. The utilization of the huge raw material potential mentioned above aimed to the development of the pellet production requires cross-disciplinary research. The subject is currently of particular importance especially in the Northern forest regions.

In addition, biotechnologically modified fiber sludge has also agricultural applications in potato production, wherein monoculture causes problems: condensing grounds, humus or soil organic matter is lost, the nutrient retention capacity is reduced, so that the leaching of nutrients grows in addition to causing financial losses to the environment (Tuomisto *et al.* 2014; Kuokkanen *et al.* 2015). Due to this, the concentration of environmental damage can be locally quite major. Environmental hazards can be reduced by using appropriate soil conditioning agents such as BMFS and other fiber sludge-based products in general because their chemical purity can be considered as a viable option in the near future. In soil structure between the soil particles, remaining mutual bonds have an essential role to help the potato plants access water and nutrients. Usable water for plants is bound to the medium-sized pores, while the macro-pores are filled with air and allow for plant root growth. In the saturated state, pores are filled with water. When soil is drying, the large pores empty first and then the small pores. In small pores, water movement is weak. Again, in sand, ground water capillary rise is strong. Potatoes are grown mainly in coarse soils with a lot of large pores. In potato production, the ground needs organic matter. For that reason, the highly potential alternative in potato production is to increase biotechnologically modified fiber sludge enhanced with appropriate nutrients into ground, wherein it operates as a scratching soil conditioning agent as well as fertilizer. In addition, the fiber sludge degrades slowly and works at the same time as a substrate (Kuokkanen *et al.* 2015). This application of BMFS is now under research and results will be published in the future.

Aim of this Work

The aim of the present research was to find and test some eco- and cost-efficient materials for binding purposes and thus improve the competitiveness of pellet products as an alternative in energy production and for bedding pellet usage. The dust binding properties of these materials in road and horse riding hall applications have also been under development and research. Therefore, the use of a locally tailored binding agent, that is biotechnologically modified fiber sludge (BMFS), has been studied and tested in this work.

EXPERIMENTAL

The most important chemical methods used in this paper, in bedding pellets particular, are shown in Table 1 and described in the following sections. These methods are described in detail in earlier publications (Kuokkanen *et al.* 2009; Kuokkanen *et al.* 2011; Kuokkanen 2013). The experiments were repeated three times and average results were presented.

Table 1. Chemical Toolbox for Research Used in Pellet Studies (Kuokkanen 2013)

Measurement	Equipment	Purpose of Determination
Moisture content	Heat oven and scales, Automatic Senfit method	Water content
Density	Solid: Laboratory compacted bulk density, SFS-EN-13040 Liquid: Densitometer	Compactness of materials
Heat value measurements	Bomb calorimeter	Energy content
BOD tests	BOD OxiTop® equipment for liquid and solid phases	Biodegradation/loss of material
Dust content, strength properties	Vibrator, sieve analysis	Mechanical stability of the pellet
Structure analysis	Staining reagents and microscope	Information about pellet structure and cross-linking mechanisms
TG analysis	Thermogravimetric analyser	Volatilisation of water and VOCs
Elementary analysis	ICP-OES	Heavy metals and/or nutrients of materials
Particle size distribution	Laser diffraction particle size analyser, image analysis	Information about particle size distribution in wood and ash

Moisture Content Measurement

Moisture content was measured according to the ISO 589 (2008) and CEN/TS 14774-1 (2004) standards. According to ISO 589 (2008), the samples were oven-dried overnight at 105 ± 2 °C to a constant mass (16 h to 24 h). According to CEN/TS 14774-1 (2004), the samples were oven-dried to a constant mass (up to 24 h) and immediately weighed when hot.

Density Measurement

Pellet bulk (solid phase) densities were measured using equipment with a measuring cylinder of 1 L and a weight of 650 g (8 g cm^{-2}), according to standard SFS-EN-13040 (1997).

Calorific Heat Measurement

Calorimetric heat measurements and calculation of net/gross calorific heat values were performed according to standards DIN 51900 (2000), ISO 1928 (1995), and ASTM D240 (2007). In this study calorific heat was determined for pellet samples with an IKA C200 calorimeter (IKA-Labortechnik, Staufen, Germany) at the Research Unit of Sustainable Chemistry, University of Oulu. The weighed portion of the analysis sample of the solid biofuel was burned in a high-pressure oxygen bomb in a bomb calorimeter under specified conditions. The effective heat capacity of the calorimeter was determined in calibration experiments by burning certified benzoic acid under conditions similar to those specified in the certificate and calculated as described in earlier publications (Kuokkanen *et al.* 2009; Kuokkanen *et al.* 2011; Kuokkanen 2013). The heat values were determined with at least duplicate measurements. However, statistical analysis was not applicable due to a small number of observation points.

BOD Measurements

Pellet samples (50 to 100 g) with a normal moisture content were first weighed and measured in MG 1.0 bottles (WTW, Weilheim, Germany) using OxiTop® Control B6M instrumentation (WTW, Weilheim, Germany; Fig. 4) (Roppola *et al.* 2006; Vähäoja 2006; Karhu *et al.* 2009; Roppola 2009). A 50-mL beaker filled with a 1 M sodium hydroxide solution was placed on a holder. The bottles were incubated at 20.0 ± 0.2 °C for 28 days.

Fig. 4. OxiTop® Control B6M instrumentation for BOD measurements in the solid phase

The BOD OxiTop apparatus for solid phase measurements is also fully automated, but it only calculates the difference in partial oxygen pressure $\Delta p(O_2)$ [hPa], from which value the degree of biodegradation [%] can be calculated as previously presented (Vähäoja 2006; Roppola *et al.* 2006; Karhu *et al.* 2009; Roppola 2009).

Mechanical Durability Measurement

The mechanical durability of the pellets was tested according to the CEN/TS 15210-1 standard (2006). Sieved double samples were tumbled in standard dimension boxes at 50 ± 2 rpm for 500 rotations and sieved. An acceptable result is more than 97.5% of the mass above the sieve. The average of the test results was used.

Elemental Analysis

The samples were extracted with MARS5 microwave wet combustion equipment (Berkeley, CA, USA) using the EPA-3051 standard method (2007). Measurements were done with a commercial plasma emission spectrometer (ICP-OES; Perkin-Elmer, Waltham, MA, USA), and the results were calculated against the sample dry weight (at 105 °C).

Dusting Measurements

Laboratory tests at the University of Oulu were carried out by the following procedure: sand samples were blown at a pressure of 1.5 bar and the dusting was determined as measured sand wastage amount [g] or relative wastage [%]. In each sample, the amount of sand was 400 g and contained a dust binding agent in different concentrations; the blowing time was held constant at 2 min. The road salt ($CaCl_2$) and water were used as the reference substances. Dust binding agents were left to dry and to affect in the sand for one day before they were measured. Sand dust was sucked with a vacuum cleaner at the same time, when it is blown into a vessel at standard blow pressure.

Run-off Experiments

Approximately 300 g of washed rubble (2 cm lower layer in column) and 150 g of normal sand (2 cm upper layer) were used in columns for modeling and determining rain water filtrates and run-offs (Fig. 5). The run-off filtrates were recovered separately from the hose in the lower part of the column system from each dust binding agent filtrate batch (30 mL of H_2O, 30 mL of road salt or $CaCl_2$, and 30 mL of BMFS). After that the rain was modeled by spraying 50 mL of water for each column with glass spray bottle and rain filtrate modeling batches were recovered again from the hose. The run-off measurements for calcium through washed rubble and normal sand were carried out by equipment presented in Fig. 5.

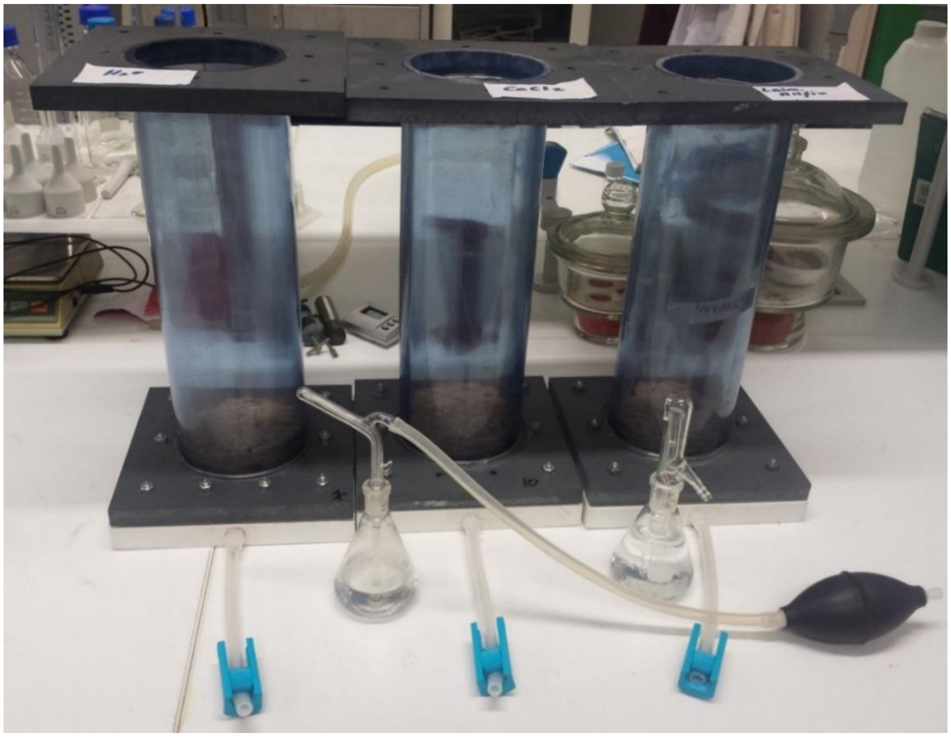

Fig. 5. The measuring columns for water, calcium chloride, and BMFS

RESULTS AND DISCUSSION

Elemental Analysis

Typical values of elements (nitrogen and heavy metal contents) in native fiber sludge (solid matter content 20%) and biotechnologically modified fiber sludge (solid matter content 3%) are presented in Table 2. The fiber sludge was from a Finnish pulp mill process rejected untreated native wood fiber. The concentration of heavy metals in BMFS were naturally much smaller than those in the native fiber sludge, as modified fiber sludge is prepared by diluting the product with water.

Table 2. Typical Values of Elements in Native Fiber Sludge and Basic Solution of BMFS

Element	Values in Native Fiber Sludge [mg/kg]	Values in BMFS Basic Solution [mg/kg]
N	4380	730
Al	2240	370
As	<3	<3
B	<4	<4
Ba	41	6.8
Be	<1	<1
Ca	45500	7600
Cd	2.1	0.35
Co	1.9	0.32
Cr	23	3.8
Cu	16	2.7
Fe	4930	820
K	<200	<200
Mg	1090	180
Mn	130	22
Mo	2.0	0.33
Na	900	150
Ni	8.7	1.45
P	730	120
Pb	6.0	1.0
S	4870	810
Sb	<3	<3
Se	<3	<3
Sn	<3	<3
Ti	65	10.8
V	2.6	0.43
Zn	340	57

Dusting Measurement

Compared with the reference materials, BMFS prevented dusting in laboratory experiments. The field tests also showed that dusting decreased in the areas where BMFS was used for dust suppression. The solid content of BMFS in laboratory tests (Tables 3 through 6) was 0.6% and in field tests 1.0%. Furthermore, in the blowing and suction experiments, small changes in the fiber sludge solid content greatly affected its dust binding efficiency. In field and laboratory tests the optimum efficiency for dust binding with BMFS was reached at 0.6% to 1.0% solid matter content (Table 7). Efficient mixing increased the functionality of BMFS as a dust-binding agent and decreased dusting for fiber sludge suspension compared to pure fiber sludge suspension (Tables 5 and 6). The results of dusting in laboratory measurements are shown in the Tables 3 through 7.

Table 3. Dusting of Normal Sand (400 g) Presented as Wastages in Laboratory Experiments

	Wastage [g]	Relative Wastage [%]
BMFS [%]		
3.75 (or 15 mL)	10.45	2.6
7.5 (or 30 mL)	10.1	2.5
15 (or 60 mL)	3.25	0.8
Road salt $CaCl_2$ [%]		
2.5 (or 10 mL)	27.8	6.9
5 (or 20 mL)	9.0	2.3
Water [%]		
12.5 (or 50 mL)	88.0	22.0

Table 4. Dusting of Riding Hall Sand (400 g) Presented as Wastages in Laboratory Experiments

	Wastage [g]	Relative Wastage [%]
BMFS [%]		
3.75	15.8	4.0
7.5	10.4	2.6
12.5	6.8	1.7
15	7.8	2.0
Water [%]		
12.5	25.2	6.3
No dust binding agent	77.7	19.4

Table 5. The Effect of Well-Mixed BMFS for Dusting in a Normal Sand (400 g)

	Wastage [g]	Relative Wastage [%]
BMFS [%]		
3.75	8.0	2.0
7.5	5.45	1.4
15	0	0

Table 6. The Effect of Well-Mixed BMFS for Dusting in Riding Hall Sand (400 g)

	Wastage [g]	Relative Wastage [%]
BMFS [%]		
3.75	26.8	6.7
7.5	19.4	4.9
15	0.1	0

Table 7. The Effect of Solid Contents of BMFS for Dusting in Normal Sand (400 g)

	Wastage [g]	Relative Wastage [%]
7.5 % (or 30 mL) BMFS [solid content-%]		
0.2	22.5	5.6
0.4	17.6	4.4
1	12.0	3.0
2	18.4	4.6
Road salt [7.5% or 30 mL]	22.0	5.5
Water [7.5% or 30 mL]	51.5	12.9
No dust binding agent	61.9	15.5

Run-off Experiments

The run-off experiments (Fig. 5) showed that using road salt ($CaCl_2$) for prevention of dusting percolated amounts of calcium that were very high compared with those using BMFS. This is a problem because increased calcium content in groundwater can have a negative impact, for example by increasing the total hardness and the carbonate hardness, which could make groundwater non-potable. A soluble chloride salt of a road salt, particularly at high concentrations, is a very harmful compound. The calcium contents of run-offs and rain filtrates of water, calcium chloride, and BMFS are presented in Table 8.

Table 8. Measured Calcium Contents of Run-Offs and Rain Filtrates of Water, Calcium Chloride, and Biotechnologically Modified Fiber Sludge

Sample	Ca [mg/L]
H_2O run-off	31
H_2O rain filtrate	29
BMFS run-off	78
BMFS rain filtrate	25
$CaCl_2$ run-off	13000
$CaCl_2$ rain filtrate	4300

Moisture Content

The measured pellet moisture contents were between 9.92% and 16.66%. In general, optimum pellet quality is obtained with a sawdust moisture content in the range of 11%-13% (Ståhl *et al.* 2004; Samuelsson *et al.* 2012; Kuokkanen 2013). Biotechnologically modified fiber sludge increased the moisture content of the pellets with the addition of this binder content. Wood chip pellets were used as a reference sample. The moisture contents of measured bedding pellets are presented in Table 9.

Table 9. Moisture Contents of Bedding Pellets from Saw Dust Using BMFS as Binding Agent

Sample (BMFS content [%])	Moisture Content [%]
Wood chip pellet (0)	9.92
Saw dust pellet (0)	11.36
Pellet (2)	12.90
Pellet (5)	13.13
Pellet (10)	16.66

Calorific Heat

Fiber sludge and its different binding agent concentrations do not appear to have a very large impact on calorific heat values of pellets (Table 10). Changes in heat values between the binding agent pellets are proportional to changes in moisture content levels (Table 9). Furthermore, if the results were to be calculated and presented to the dry matter of the calorific value, the calorific heat results would be virtually the same for all measurements. Statistical analysis was not applicable due to a small number of observation points. This is logical, because the added quantity of the binding agent in each pellet studied was very small relative to the amount of biomass. Wood chip pellets were used as reference sample.

Table 10. Calorific Heat Values of Bedding Pellets from Saw Dust

Sample (BMFS Content [%])	Calorific Heat Value [MJ/kg]
Wood chip pellet (0)	18.77
Saw dust pellet (0)	18.53
Pellet (2)	18.50
Pellet (5)	17.95
Pellet (10)	17.31

Bulk Density

Bulk density has a direct connection to the pellet strength because it indicates how tightly the pellet is compressed. Bulk density measurements were carried out for raw materials of pellets and binding agent BMFS. Bulk densities of pellets were between 413 g/L and 626 g/L. The bulk density of raw material saw dust was significantly lower than the corresponding value of reference material wood chips (Table 11). The wood chips require a thinner matrix (8/35 mm) than saw dust (8/55 mm) for the pelletizing process to succeed. This requirement can be explained by the larger particle size of wood chips compared to the other raw materials, which can be observed also from the bulk density results. Nevertheless, the highest bulk density values of the pellets were accomplished by compressing low bulk density raw materials, such as pellets with BMFS content of 2% and pellets with no binding agent. Instead a greater proportion of higher bulk density wood chips as raw material for pellets reduced the bulk density of the pellets. When a higher concentration of fiber sludge was added to saw dust, the bulk density of pellets decreased.

Table 11. Bulk Densities of Bedding Pellets from Saw Dust and their Raw Material

Sample (BMFS Content [%])	Bulk Density of Pellet [g/l]	Raw Material [g/l]
Wood chip pellet (0)	412.99	231.03
Saw dust pellet (0)	622.91	78.64
Pellet (2)	625.99	99.51
Pellet (5)	571.55	100.95
Pellet (10)	493.44	102.68

BOD Measurements

In biodegradability test of 28 days (BOD_{28}), pellets with no binding agent and pellets with BMFS content of 5% were measured. Pellets with BMFS did not biodegrade at all within measurement accuracy limits during the 28-day research period. This is very similar to the results in earlier observations (Kuokkanen 2013). Biodegradation of pellets and their raw materials is a very important factor in full-scale industrial manufacture of pellets, as high biodegradability may cause considerable economic losses during storage and transportation, causing also mechanical decomposition of pellet products and formation of volatile harmful compounds as decomposition of pellet biomass may produce dangerous quantities of carbon monoxide and hexanal during pellet storage (Svedberg *et al.* 2004; Ahonen and Liukkonen 2008; Svedberg *et al.* 2008).

Mechanical Durability

The effects of the cohesive properties and mechanical strength of fiber sludge can be observed from the mechanical durability results presented in Table 12. Wood chip pellets were used as reference sample. Fiber sludge achieved a small positive effect on cohesion characteristics, however the result was better with a lower addition of BMFS binding agent. The effect of the optimum moisture content for both the bulk density and the mechanical durability was noticeable. Mechanical durability of measured bedding pellets are presented in Table 12.

Table 12. Mechanical Durability of Bedding Pellets from Saw Dust

Sample (BMFS Content [%])	Mechanical Durability [%]
Wood chip pellet (0)	73.43
Saw dust pellet (0)	98.88
Pellet (2)	98.60
Pellet (5)	97.37
Pellet (10)	95.34

It is important and justified to carry out further tests for this ecological dust-binding substance in full scale and to develop for it an appropriate spraying system. The utilization of BMFS as a dust binding agent in road construction and mining industry dust suppression will be studied in the near future.

CONCLUSIONS

1. The native wood fiber sludge as a raw material of BMFS is an aqueous, chemically pure waste material (Table 2) and therefore very environmentally friendly for raw materials, for example in different binding agent applications.
2. The BMFS proved in all laboratory measurements and field experiments to be a very effective and efficient dust-binding agent.
3. BMFS is an efficient binding agent for both combustion and bedding pellets.
4. Due to different requirements of properties, applications of BMFS in pellet usage have optimal binding agent contents as follows: bedding pellet (5 to 10%) and combustion pellet (1 to 2%).
5. Furthermore, different application requirements of BMFS have different optimum dry matter contents as observed in field and laboratory tests: 5 to 10% for bedding and combustion pellet and 0.6 to 1.0% for dust binding agent.
6. The efficient mixing increases the functionality of BMFS as a dust-binding agent.
7. Run-off experiments proved that BMFS is an ecological option for road dust suppression compared to generally used road salt ($CaCl_2$).
8. In BOD_{28} tests, pellets with BMFS did not biodegrade at all in the 28-day research period, which is a positive aspect considering transportation and long-term storage of pellets.

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