



The Use of Wood Biomass Ash in Sewage Sludge Treatment in Terms of Its Agricultural Utilization

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Abstract

Due to inappropriate agricultural treatments, soils often turn into wastelands. After years, the return to cultivation is very difficult or even impossible. It is a serious problem for agriculture, also in Poland. In order to improve soil quality and to restore its value in use, different fertilizers are commonly used. As an alternative for artificial fertilizers, sewage sludge and biomass ashes might be applied. High cost of sewage sludge conditioning with the use of polyelectrolytes has resulted in the development of research dedicated to finding new and inexpensive conditioners. The article discusses the possibility of sludge conditioning by means of wood biomass ash. In the paper, the findings of sewage sludge dewatering with the use of wood ash on a laboratory and on a technical scale are presented. The analysis of results has shown that the addition of wood biomass ash improved sludge dewatering by 10–23% in a laboratory scale and by 15–27% on a technical scale. The application of wood ash also reduced the total bacteria number by 83–89% in a laboratory scale and by 40–53% on a technical scale. Additionally, the obtained mixture of sewage sludge and wood biomass ash might be applied in agricultural practices, especially in fertilizing perennial plants plantations. Thanks to that it is possible to obtain inexpensive and valuable natural fertilizer while reducing costs of sludge dewatering.

Keywords Sewage sludge · Wood biomass ashes · Dewatering · Conditioning · Higienization · Fertilizer

Statement of Novelty

In the submitted paper, the unconventional method of sewage sludge conditioning with the use of wood biomass ash was presented. The aim of this manuscript is to describe the effect of wood ash on the improvement of sewage sludge dewatering and higienization, both in a laboratory and on a technical scale. Different parameters characterized the effectiveness of sewage sludge dewatering and higienization are presented. Biomass combustion by-products might be considered as an alternative reagent for traditional conditioners, which are commonly applied in treatment plants. Additionally, the final product of sludge dewatering, namely

the mixture of sewage sludge and wood ash, can be used as a natural fertilizer improving the plant growth. The sewage sludge conditioning by means of wood biomass ashes and the possibility of the application of mixture is a new solution in sewage sludge management.

Introduction

The world population growth, from approximately 3 billion in 1970 to 7.6 billion people in 2017, requires meeting essential food needs. Demographic forecasts indicate that human population will grow to 9.5 billion by 2050 and to 12 billion by 2100. It means that world food production might increase by over 50% [1]. The increased demand for food implies the development of many sectors of economy related to food production, such as agriculture. The available data indicate that the growth of world production causes the decline of arable land surface per capita from 0.42 ha in 1960 to 0.20 ha in 2010 [2]. For this reason, meeting global food demands might be achieved by proper agricultural practices and intensive fertilizing of plants.

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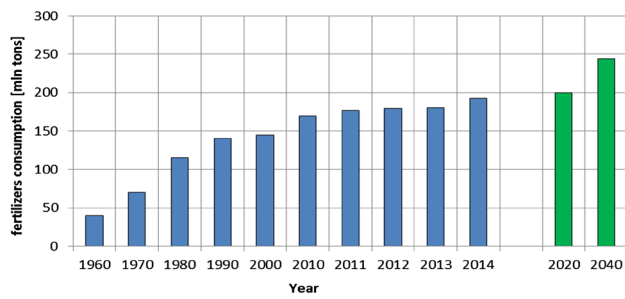


Fig. 1 The worldwide fertilizers consumption over the period of 1960–2014 with projections to 2040 [2, 3]

According to Zalewski [2], the total production of fertilizers was approximately 192 million tons in 2012 while the level of consumption was 179 million tons. In comparison to 1960, the worldwide fertilizer consumption increased even fivefold (Fig. 1). The fertilizers consumption was 180 and 193 million tons in 2013 and 2014, respectively. The statistics also predict that the total consumption of fertilizers will be approximately 200 million tons in 2020 and approximately 250 million tons in 2040 [3].

The cost of fertilizing is one of the most important costs in agricultural practices. Depending on the kind of fertilizers, the cost is in the range of EURO 100–600 per ton of fertilizer [4]. In order to decrease the cost of acquiring of fertilizers, waste and other by-products are used in agriculture. It was proved that different waste had a positive impact on the soil properties, as well as the plant growth (Table 1). Additionally, the agricultural application

Table 3 The influence of sewage sludge on physical, chemical and microbiological properties of soil [15–18]

| Properties | Effect |
|--------------------------|----------------------|
| pH | Decrease or increase |
| Soil aggregate stability | Increase |
| Bulk density | Decrease |
| Water holding capacity | Increase |
| Porosity | Increase |
| Humus content | Increase |
| Soil organic carbon | Increase |
| Content of P and N | Increase |
| Cation exchange capacity | Increase |

enables to manage some problematic waste, for example sludge and to obtain inexpensive and valuable fertilizers.

Properly prepared sewage sludge might be applied in agriculture as a substitute of other organic fertilizers, which is commonly practiced in many European countries (Table 2). Soil conditions can be successfully improved by the sewage sludge application. The literature review confirmed the positive impact of sewage sludge on the growth of plants, the reclamation of degraded lands and the improvement of other properties of soil [11–18] (Table 3).

The main advantage of the agricultural use of sewage sludge is its fertilizing properties, especially the content of organic matter, nitrogen, phosphorus and other microelements (Table 4) [20]. Additionally, the agricultural utilization of sewage sludge is characterized by the lowest cost (Table 5) in comparison to other methods, for example

Table 1 Examples of the application of different fractions of waste in agricultural practices

| Kind of waste | Results | References |
|-----------------------|---|------------|
| Paper sludge | Improvement the growth of shrub willow | [5] |
| Composted green waste | The growth of pH of soil The increase of nutrient level in soil | [6] |
| Marine waste | The increase of plants shoot and root length | [7] |
| Biogas residues | The increase of plant growth The increase of nitrogen mineralization capacity and potential ammonium oxidation rate in soil | [8] |
| Coal fly ashes | The improvement of soil characteristics | [9] |
| Municipal waste | The enhancement of the levels of organic matter, total nitrogen and available phosphorus in soil The increase of a content of trace elements in soil | [10] |

Table 2 The use of sewage sludge in agriculture in selected European Countries in 2013 [19]

| | European country | | | | | | | |
|--|------------------|---------|--------|--------|--------|----------|--------|-------------------|
| | Germany | Estonia | France | Latvia | Poland | Slovakia | Norway | Switzerland |
| Use of sewage sludge in agriculture [10^3 tons] | 491.30 | 0.29 | 368.60 | 7.50 | 105.40 | 0.52 | 82.60 | 0.00 ^a |

^aFrom 2006, only thermal sewage sludge utilization methods are acceptable

Table 4 Composition of sewage sludge according to different authors

| Constituent | References | | | | |
|--|------------|-------|-------|-------|-------------|
| | [22] | [23] | [24] | [25] | [26] |
| Organic matter [% d.m.] | 45.30 | – | 43.10 | 41.00 | 11.00–51.00 |
| Total C [% d.m.] | 22.10 | 32.51 | – | – | 5.00–25.00 |
| Total N [% d.m.] | 2.10 | 4.85 | 1.81 | 3.90 | 0.80–1.90 |
| Total P ₂ O ₅ [% d.m.] | 2.20 | – | 2.52 | 0.50 | 1.10–1.30 |
| Total K ₂ O [% d.m.] | 0.97 | 1.56 | – | – | 0.28 |
| Total CaO [% d.m.] | 7.06 | 2.35 | 2.83 | 1.70 | 0.51 |
| Total MgO [% d.m.] | 1.72 | 0.92 | 0.31 | 0.60 | 0.14 |
| Total Na ₂ O [% d.m.] | 0.07 | 0.21 | – | – | 0.07 |

Table 5 Average cost of sewage sludge utilization in European Countries [19]

| Method | Average cost [EURO/ton d.m.*] |
|-------------------------------|-------------------------------|
| Agricultural use | 160 |
| Drying | 210 |
| Forestry | 240 |
| Composting | 310 |
| Combustion | 315 |
| Declamation of degraded lands | 255 |
| Landfilling | 255 |

d.m. dry mass

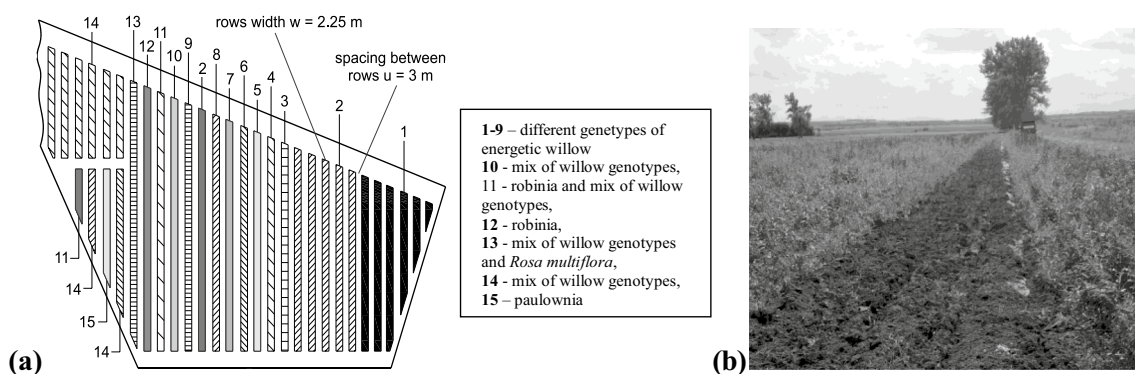
combustion, drying or composting [21]. On the other hand, it is necessary to include legal requirements associated with the content of heavy metals and pathogens. Additionally, sewage sludge might have proper consistence convenient to transport and application. Recently, the content of heavy metals in sewage sludge has decreased; for this reason, the agricultural utilization of sewage sludge is the most rational method, especially for small and medium treatment plants [11].

Due to the presence of organic and mineral compounds, sewage sludge might be applied in fertilizing of energetic and industrial crops. Urbaniak et al. [27] and Záltauskaitė et al. [28] proved the positive impact of the application of sewage sludge on willow growth and metabolism. Additionally, the aforementioned method enriches soil in valuable elements. In fertilizing of energetic plants, the following consistence of sewage sludge could be used [29]:

- liquid sewage sludge, which delivers nutrients for plant's growth,
- solid sewage sludge, which enables soil improvement and the reclamation of degraded lands,
- sewage sludge with greasy consistence, which enables to create the coat covering mineral soil.

The non-consumption character of energetic waste causes, that the content of heavy metals in sewage sludge does not matter for using value of yields. The risk associated with the application of sewage sludge in perennial plants plantations is restricted due to the exclusion of energetic plants from human trophic chain. For this reason, the traditional mineral fertilizing might be improved and even replaced with properly prepared sewage sludge. The research concerning the use of sewage sludge in perennial plant plantations was carried out by Rzeszow University of Technology. The experimental plantation of the total area of 30 ha was located in Świlcza (Poland) (Fig. 2). The results of the research indicated that the addition of sewage sludge did not influence the increase of the content of heavy metals in soil [30]. The concentration of heavy metals in soil did not exceed the limited values determined by Regulation 1395 (2016) of the Minister of the Environment [31], which are: < 150 mg/kg for Cr, < 300 mg/kg for Zn, < 2 mg/kg for Cd and Hg, < 20 mg/kg for Co, < 100 mg/kg for Cu, Ni and Pb.

The use of sewage sludge for agricultural purposes requires laying it at proper depth, and covering it with soil. Such treatments do not permit commercially available

**Fig. 2** Energetic plant plantation in Świlcza: scheme (a) and view after subsurface application of sewage sludge (b)

fertilizer spreaders. In line with the law concerning the sewage sludge management, Rzeszow University of Technology has designed a device for injection dosage of organic and mineral fertilizers (Fig. 3). The device developed according to the patent PL 382 062 is a part of the stock of machines devised at Rzeszow University of Technology, which compared with the commonly used fertilizer spreaders provides immediate coverage of soil fertilizer. This device has a beneficial effect on the environment. The device combines the process of fertilization and transport of sewage sludge, allowing for its placing to the desired depth of about 5–25 cm and simultaneously covering sludge with a layer of soil. The special construction of this machine also eliminates the danger of possible sewage sludge leakage and reduces the odor nuisance. The aforementioned advantages of the device cause that the fertilizing with the use of sewage sludge is less disruptive both for people and environment.

Due to the fact that the spacing of the tools equals 0.7 m, this device is ideal for fertilizing energy plants plantations. Such a layout of tools corresponds to the typical system of willow plants. Furthermore, the module could be attached to traditional fertilizer spreaders without any special modification of the device. Detailed information concerning the aforementioned device is included in other research articles [29, 30, 32].

Biomass combustion by-products also present valuable fertilizing properties. The application of biomass ashes increased the content of Ca, Mg, P and Na in soils improving plants growth [33–35]. By means of that, the research concerning the sewage sludge conditioning with the use of biomass ashes and the agricultural application of the obtained mixture of sewage sludge and ash was performed. Synergistic effect of ashes and sludge might ensure the higher effectiveness in terms of plants yield in comparison to the use of only one material. Additionally, the mixture of sewage sludge and biomass ashes could be applied as a natural and mineral fertilizer or as a reclamation substance. Last but not least, the growing consumption of biomass in energy sector results in the production of

combustion by-products. Currently, energy obtained from biomass constitutes approximately 8–15% of final energy production. It is estimated that such amount will increase to 33–50% by 2050 [16]. For this reason, new methods of utilization in compliance with economical, legal and environmental requirement are required. The application of biomass ashes in sewage sludge management and the use of the obtained mixture in agriculture enable to manage two kinds of problematic waste in accordance with the aforementioned requirements.

As stated above, liquid or solid sewage sludge might be used in agricultural practices. But solid consistence of sludge is the most convenient for transport or fertilizing. However, raw sewage sludge might deform under high pressure and for this reason, the effectiveness of sludge dewatering is relatively low. In order to improve the water removal from sewage sludge, physical and chemical conditioners are commonly applied. Physical conditioners (*filter aids* or *skeleton builders*) are inert solid materials which reduce the compressibility of sludge and improve the mechanical strength of flocs. The addition of filter aids can dramatically decrease the sludge compressibility under mechanical pressure [36]. In literature, different materials were tested as physical conditioners, for example coal fly ash [37], lignite [38], red mud [39], rice husk [40] or wood chips [41]. In authors previous studies, sewage sludge was conditioned with the use of willow ash [42] and beech wood ash [43]. The results obtained by different authors showed that the addition of various physical conditioners improved the effectiveness of sewage sludge dewatering.

This article presents the results of sewage sludge conditioning and dewatering with the use of wood biomass ash, both on a laboratory and on a technical scale. The influence of wood ash on the content of microorganisms in sewage sludge was also tested. Studied found the improvement of sewage sludge dewatering after the addition of wood ash. Additionally, the application of the aforementioned ash resulted in the decrease of total bacteria number in comparison to raw sewage sludge. All these results show a great

Fig. 3 Prototype of the device for subsurface application of loose organic and mineral fertilizers manufactured by SIPMA S.A.: 1—trailer, 2—base frame, 3—beam, 4—arms, 5—loading chamber, 6—hydraulic cylinder, 7—disc coulters, 8—flap, 9—screw conveyor, 10—cylindrical housing of screw conveyor, 11—ridging plough, 12—hydraulic engine



potential of wood biomass ashes in sewage sludge management and in fertilizing energetic plant plantations.

Materials and Methods

Research concerning the influence of wood biomass ashes on sewage sludge dewatering was done for sewage sludge coming from the thickening tank in Świlcza Wastewater Treatment Plant (WTP) (Podkarpackie region, Poland). In a research, sewage sludge after stabilization and thickening was used. For the obtained sewage sludge; physical, chemical and microbiological characteristics were determined according to the applicable methodology (Table 6).

In the research concerning the sewage sludge conditioning, wood biomass ash coming from “Łężańska” Power Plant in Krosno (Podkarpackie region, Poland) was used. Aforementioned ash is the result of wood biomass combustion in a boiler using Organic Rankine Cycle (ORC) technology. Physical properties and chemical composition of wood ash were determined according to the methodology presented in Table 7.

Both tests carried out in a laboratory and on a technical scale were done in three series according to the scheme below (Fig. 4).

The following laboratory research was carried out: five beakers of the volume of 1 dm³ were filled with 500 cm³ of raw sewage sludge. The appropriate dosages of wood ash were added to four of them (Table 8). The dosages were established on the basis of an initial research, as well as the literature review [30, 31, 35]. Firstly, beakers were rapidly stirred at the speed of 200 rpm for 1 min and then, they were stirred at the speed of 50 rpm for 15 min. After that, prepared samples of sewage sludge were dewatered by means of vacuum filtration and pressure filtration. The vacuum filtration was done under 0.01 and 0.02 MPa vacuum pressure by means of a porcelain Buchner funnel (d=9 cm) (Kartell Labware, Italy). The pressure filtration was performed under 0.1 MPa with the application of pressure filter (d=50 mm) (SATORIUS, Poland). After dewatering, the final hydration and capillary suction time (CST) were determined according to the applicable methodology (see Table 7). The influence of wood biomass ash on microbiological characteristics of sewage sludge was also concluded. In all the cases, the reference level was non-conditioned sewage sludge.

The results obtained in laboratory research were verified in tests performed on a technical scale. This stage of research was done in Świlcza WTP with the use of MONOBELT NP-15 filter belt press. Due to the highest effectiveness of dewatering in a laboratory, research was performed for the highest tested dosages of wood biomass ash (15 and 30 g/

Table 6 Determination of the parameters of sewage sludge

| Parameter | Unit | Method | Procedure |
|-----------------------|--------------------|---------------------------|--------------------------|
| pH | – | Electrometric | PN-EN 15933:2013-02 [44] |
| Moisture content | % | Weight method | PN-EN 12880:2004 [45] |
| CST | s | Quality method | PN-EN 14701-1:2007 [46] |
| Total bacteria number | cfu/g | Plate method | PN-EN ISO 6222:2004 [47] |
| Chemical composition | % d.m., mg/kg d.m. | Spectrometric method, AAS | PN-EN 13657:2006 [48] |

CST capillary suction time, AAS atomic absorption spectrometry, cfu colony forming unit, d.m. dry mass

Table 7 Determination of the parameters of wood ash

| Parameter | Unit | Method | Equipment | Procedure |
|------------------------|-------------------|---------------------------|---|---|
| Density | g/cm ³ | Pycnometer method | Pentapyc 5200e density analyzer (Quantachrome Company, USA) | PN-EN 196-5:2011 [49] |
| Specific surface area | m ² /g | BET method | NOVA Model 4200 Area Analyzer (Quantachrome Company, USA) | PN-EN 196-6:2011 [50] |
| Granulometric analysis | μm | Laser diffraction method | MALVERN SIZER 2000 (Malvern Instruments, UK) | ISO 13320-209 [51] |
| VMD, SMD | μm | Laser diffraction method | MALVERN SIZER 2000 (Malvern Instruments, UK) | ISO 13320-209 [51] |
| Chemical composition | % | X-ray fluorescence method | 2830 ZT Wafer Analyzer (Malvern Panalytical Ltd., UK) | ISO 29581-2:2010 [52], PN-EN ISO 12677:2011 [53], PN-EN 196-2:2013 [54] |

VMD volume mean diameter, SMD surface mean diameter

Fig. 4 Stages of research

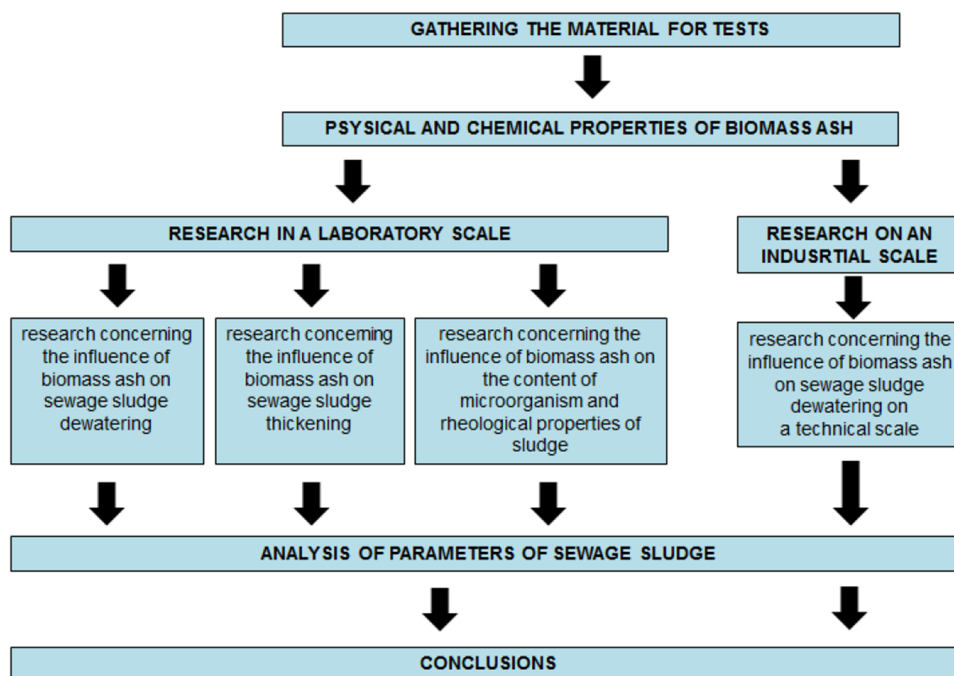


Table 8 Dosages of wood ashes used in laboratory studies

| Wood ash dosages | Beaker's number | | | | |
|-----------------------------|-----------------|-------|-------|-------|--------|
| | 0 | 1 | 2 | 3 | 4 |
| Dosage [g/dm ³] | – | 5.0 | 7.5 | 15.0 | 30.0 |
| Mass dosage [g/kg d.m.] | – | 317.6 | 476.3 | 952.7 | 1905.4 |
| Percent dosage [% d.m.] | – | 31.8 | 47.7 | 95.3 | 190.6 |

Table 9 Dosages of reagents used in tests on a technical scale

| Reagent dosages | Variant | | | |
|---------------------------------------|---------|------|------|----------------------------------|
| | 0 | 1 | 2 | 3 |
| Wood biomass ash [g/dm ³] | – | 15.0 | 30.0 | – |
| Polyelectrolyte [mg/g d.m.] | – | – | – | 4.0 (0.12 g/dm ³) |

dm³). The reference level was non-conditioned sewage sludge and sewage sludge conditioned by means of polyelectrolyte Propam Ebo 4800, which is commonly used in the aforementioned treatment plant. Details concerning conditioners and the dosages of reagents used in tests on a technical scale are presented in Table 9.

After dewatering by means of a filter belt press, CST and final moisture content were determined in line with the methodology presented in the table above (see Table 7). For the obtained mixture of sewage sludge and wood ash, the total bacteria number was also stated. The chemical

composition of the aforementioned mixture was also determined by means of spectrometric method.

The obtained results were analyzed with the use of Analysis of Variance (ANOVA). In order to check the linear relationship between parameters of sludge, the Pearson correlation was used. The α and p values were determined with the application of STATISTICA at the level of $\alpha = 0.05$.

Results

Characteristics of Sewage Sludge and Wood Biomass Ash

Characteristics of sewage sludge are shown in Table 10. The parameters have a similar value both for sewage sludge used in laboratory tests and for sludge used in tests on a technical scale. The results obtained within this study indicate a relatively high content of calcium in sewage sludge. Sewage sludge also contained nitrogen, which is necessary for the proper functioning of soil ecosystem. Regarding the content of heavy metals, Zn, Cu, Pb and Cr were dominant in sewage sludge. Nevertheless, the concentration of heavy metals was lower than the limit values defined in Polish regulations [55]. According to Grzybek [56], approximately 75% of sewage sludge generated in treatment plants in Poland meets the requirements concerning the content of heavy metals and microorganisms. It enables agricultural application of sewage sludge from Świlcza WTP without the environmental risk.

Table 10 Characteristics of raw sewage sludge used in the studies

| Parameter | Unit | Sewage sludge | | Limits according with [55] |
|-----------------------|-------------------|------------------|-----------------|----------------------------|
| | | Laboratory scale | Technical scale | |
| pH | – | 6.40±0.13 | 6.98±0.13 | – |
| d.m. | % | 2.52±0.55 | 2.71±0.55 | – |
| Concentration of d.m. | g/dm ³ | 25.20±5.45 | 27.10±5.45 | – |
| Initial hydration | % | 97.48±0.55 | 97.29±0.55 | – |
| CST | s | 130.89±11.35 | 158.03±11.35 | – |
| Organic matter | % d.m. | 48.50±9.80 | 57.30±9.80 | – |
| Total N | % d.m. | 3.75±0.77 | 4.24±0.77 | – |
| Total P | % d.m. | 1.68±0.10 | 2.11±0.10 | – |
| Ammonium nitrogen | % d.m. | 0.09±0.04 | 0.15±0.04 | – |
| Total Ca | % d.m. | 5.53±1.40 | 8.68±1.40 | – |
| Total Mg | % d.m. | 0.32±0.08 | 0.49±0.08 | – |
| Zn | mg/kg d.m. | 605±17.55 | 616±17 | <2500 |
| Pb | mg/kg d.m. | 7.98±1.71 | 10.50±1.71 | <750 |
| Cr | mg/kg d.m. | 7.42±1.53 | 8.35±1.53 | <500 |
| Cu | mg/kg d.m. | 89.34±19.0 | 97±19 | <1000 |
| Ni | mg/kg d.m. | 6.10±1.23 | 8.60±1.23 | <300 |
| Cd | mg/kg d.m. | 0.43±0.11 | 1.63±0.11 | <20 |
| Hg | mg/kg d.m. | 0.24±0.06 | 0.19±0.06 | <16 |

Detailed physical and chemical characteristics of wood biomass ash are presented in the table below (Table 11). The obtained results indicated high content of calcium and potassium. According to Poluszyńska [57], ashes obtained from the combustion of pine wood chips or beech chips also contained approximately 44% of Ca and 10% of K, respectively. Waclawowicz [58] showed that willow wood ash was characterized by the content of Ca and K at the level of 45 and 8%, respectively. Low concentration of heavy metals (below 0.5%) enables agricultural application of the aforementioned ash according to Polish regulations [59].

The Influence of Wood Biomass Ash on Sewage Sludge Dewatering and Higienisation on a Laboratory Scale

The results obtained in laboratory research have shown that sewage sludge conditioning with the use of wood biomass ash had a positive impact on sewage sludge dewatering measured by means of final hydration and CST (Table 12). Raw sewage sludge indicated low-dewatering capacity, which was proved in the filtration process. The moisture content of non-conditioned sewage sludge decreased of only 3.4% after pressure filtration and by approximately 9.2–9.6% after vacuum filtration. Low filterability of raw sewage sludge was also proved by Wu et al. [60], who achieved only 5% reduction of sludge moisture content. Yang et al. [61] showed that non-conditioned sewage sludge decreased the moisture content after dewatering by 3%.

Table 11 Characteristics of wood biomass ash used in research

| Parameter | Unit | Value |
|--------------------------------|-------------------|-------------|
| Physical properties | | |
| Density | g/cm ³ | 2.59±0.11 |
| Specific surface area | m ² /g | 1.88±0.04 |
| VMD* | µm | 38.84±0.45 |
| SMD* | µm | 9.10±0.11 |
| Chemical characteristics | | |
| CaO | % | 45.84±0.10 |
| SiO ₂ | % | 15.37±0.10 |
| K ₂ O | % | 9.88±0.09 |
| SO ₃ | % | 7.61±0.08 |
| P ₂ O ₅ | % | 4.58±0.06 |
| MgO | % | 4.24±0.06 |
| Al ₂ O ₃ | % | 4.14±0.06 |
| Fe ₂ O ₃ | % | 3.85±0.06 |
| Cl | % | 1.63±0.04 |
| MnO | % | 1.61±0.04 |
| ZnO | % | 0.41±0.02 |
| Na ₂ O | % | 0.40±0.02 |
| SrO | % | 0.15±0.01 |
| ZrO | % | 0.10±0.01 |
| CuO | % | 0.03±0.01 |
| PbO | % | 0.03±0.01 |
| NiO | % | 0.01±0.01 |
| CdO | % | 0.009±0.002 |
| Br | % | 0.005±0.002 |

Table 12 Influence of wood biomass ash application on sewage sludge dewatering capacity (laboratory scale)

| Parameter | Unit | Dosage of wood ash [g/dm ³] | | | | |
|--|------|---|--------------|--------------|--------------|--------------|
| | | 0.0 | 5.0 | 7.5 | 15.0 | 30.0 |
| Pressure filtration | | | | | | |
| Initial moisture content | % | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 |
| Final moisture content | % | 94.12 ± 1.27 | 91.89 ± 0.62 | 89.87 ± 1.91 | 87.04 ± 1.91 | 83.40 ± 2.88 |
| Moisture content reduction | % | 3.36 ± 1.13 | 4.87 ± 1.20 | 6.73 ± 2.68 | 8.51 ± 2.73 | 10.74 ± 3.20 |
| Moisture content reduction per gram of added ash | % | – | 0.97 | 0.90 | 0.57 | 0.36 |
| CST | s | 2034 ± 343 | 2371 ± 253 | 2585 ± 207 | 2937 ± 76 | 3229 ± 210 |
| CST per gram of added ash | s | – | 474 | 345 | 196 | 108 |
| Vacuum filtration (0.01 MPa) | | | | | | |
| Initial moisture content | % | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 |
| Final moisture content | % | 88.21 ± 1.98 | 85.42 ± 3.00 | 84.19 ± 2.19 | 80.16 ± 4.02 | 75.64 ± 5.19 |
| Moisture content reduction | % | 9.27 ± 2.22 | 11.34 ± 3.46 | 12.42 ± 2.49 | 15.39 ± 2.46 | 18.51 ± 3.51 |
| Moisture content reduction per gram of added ash | % | – | 2.27 | 1.66 | 1.03 | 0.62 |
| CST | s | 4035 ± 256 | 4351 ± 552 | 4424 ± 616 | 4627 ± 796 | 5014 ± 164 |
| CST per gram of added ash | s | – | 870 | 590 | 308 | 167 |
| Vacuum filtration (0.02 MPa) | | | | | | |
| Initial moisture content | % | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 | 97.48 ± 0.81 |
| Final moisture content | % | 87.94 ± 2.29 | 83.07 ± 3.95 | 82.02 ± 4.00 | 76.07 ± 5.00 | 70.91 ± 4.00 |
| Moisture content reduction | % | 9.54 ± 2.51 | 13.69 ± 4.37 | 14.58 ± 4.38 | 19.48 ± 3.34 | 23.23 ± 3.23 |
| Moisture content reduction per gram of added ash | % | – | 2.74 | 1.94 | 1.30 | 0.77 |
| CST | s | 4069 ± 429 | 4542 ± 272 | 4790 ± 397 | 5263 ± 176 | 6047 ± 134 |
| CST per gram of added ash | s | – | 908 | 639 | 351 | 202 |

The addition of wood biomass ash to sewage sludge decreased the final moisture content due to formation of special skeleton builder for sludge particles. Depending on dewatering techniques and the applied dose of wood biomass ash, the sewage sludge moisture content had differential values. The application of wood ash from biomass-fired power plant reduced the sewage sludge moisture content after pressure filtration by approximately 5–11%, depending on the dosage of wood ash. The addition of the aforementioned reagent could lead to obtaining the final hydration of sewage sludge at the level of 83.4–1.9%. The best results were achieved for 30 g/dm³ dosage of wood ash, which could decrease the moisture content from approximately 97.5% (raw sewage sludge) to 83.4% (conditioned sewage sludge). Low doses of wood biomass ash did not influence the change of sludge hydration.

In laboratory research, the most effective method of sewage sludge dewatering was the vacuum filtration. The application of wood biomass ash intensified the vacuum filtration depending on the applied dosage of ash. Generally, the sewage sludge moisture content decreased as the dose of wood ash increased. The average sewage sludge moisture content after vacuum filtration for the vacuum pressure of 0.01 MPa was at the level of 75.6–85.4%. The results correspond to the moisture content reduction of approximately 11–19%, depending on the dosage of ash. The change of

vacuum pressure improved the effectiveness of sludge dewatering. For the higher vacuum pressure value (0.02 MPa), the sewage sludge moisture content decreased of approximately 13.7–23.2% to the value in the range of 70.9–83.1%. In contrast to pressure filtration, the addition of wood biomass ash resulted in the decline of moisture content in the whole range of dosages. However, the best results were obtained for 30 g/dm³ dose of wood ash.

The efficiency of sewage sludge dewatering after conditioning with the use of wood ash was also expressed by the moisture content reduction per gram of added ash. In this case, the sludge moisture content reduction decreased with the increase of a dosage of ash. It confirms the lack of linear relationship between dosage of wood ash and the sludge moisture content reduction. It was observed for all tested dewatering methods, but the lowest differences were noted for sludge dewatering by means of pressure filtration. For 5, 7.5, 15 and 30 g/dm³ dosages of ash, the moisture content reduction per gram of ash was 0.97, 0.90, 0.57 and 0.36, respectively. Higher differences between samples of sludge were noted for vacuum filtration. For 5, 7.5, 15 and 30 g/dm³ dosages of ash, the values of the moisture content reduction per gram of ash were 2.27, 1.66, 1.03 and 0.62 (0.01 MPa) and 2.74, 1.94, 1.30 and 0.77 (0.02 MPa). The change of vacuum pressure resulted in the improvement of sludge dewatering expressed by the moisture content reduction per

gram of added ash. Similarly to the moisture content, the application of wood ash into sewage sludge resulted in the decrease of CST per gram of added ash. The analysis of results showed that CST per gram of applied ash decreased as the dosage of wood ash increase. These results presented that the increase of a dosage of wood ash not lead directly to the improvement of sludge dewatering.

The results of laboratory tests were compared with the findings obtained by other authors (Table 13). The literature review shows significant influence of ash originated from different biomass in terms of sewage sludge processing. Wójcik et al. [42, 43] reported that the addition of willow and beech wood ash in the dosages of 5–30 g/dm³ influenced on the effectiveness of vacuum filtration in a comparable degree to a laboratory research. Chen et al. [37] proved that the application of coal fly ash in the dosage of 82.7 g/dm³ can decrease the final sewage sludge moisture content by approximately 46%. Zhu et al. [36] also noted that previous

sludge conditioning with the use of rice husk decreased the moisture content by 30%. But chemical conditioners might improve the sludge dewatering to the higher extent than biomass ashes. Bień [62] noted that the application of cationic polyacrylamide in a dosage of 5 mg/g d.m. resulted in the decrease of sludge moisture content by approximately 30%. According to Wu et al. [60], ashes are only neutral materials which influence only the strength of flocs and the improvement of permeability of sludge. For this reason, their influence the improvement of sludge dewatering might be lower than chemical reagents.

The susceptibility of conditioned sewage sludge to further water removal was assessed by means of capillary suction time measurement (see Table 11). Increasing wood ash dosage caused an increase of CST but the highest values of the aforementioned parameter were achieved for sewage sludge conditioned by the use of wood ash in the amount of 30 g/dm³. Depending on the method of filtration, CST for the

Table 13 Influence of different energetic waste on the improvement of sewage sludge dewatering

| Kind of waste | Dewatering method | Material dosage [g/dm ³] | Sewage sludge moisture content reduction [%] | Sewage sludge moisture content reduction per gram of added ash [%] | References |
|-----------------|------------------------------|--------------------------------------|--|--|------------|
| Coal fly ash | Vacuum filtration (0.03 MPa) | 0.0 | 11.99 | – | [37] |
| | | 35.5 | 36.59 | 1.03 | |
| | | 59.2 | 42.76 | 0.72 | |
| | | 82.7 | 46.32 | 0.56 | |
| Willow ash | Vacuum filtration (0.02 MPa) | 0.0 | 8.63 | – | [42] |
| | | 5.0 | 11.33 | 2.27 | |
| | | 7.5 | 13.50 | 1.80 | |
| | | 15.0 | 17.05 | 1.14 | |
| | | 30.0 | 21.72 | 0.72 | |
| Willow ash | Centrifugation (2500 rpm) | 0.0 | 5.48 | – | [42] |
| | | 5.0 | 7.16 | 1.43 | |
| | | 7.5 | 8.51 | 1.13 | |
| | | 15.0 | 11.22 | 0.75 | |
| | | 30.0 | 14.85 | 0.50 | |
| Wheat straw ash | Vacuum filtration (0.01 MPa) | 0.0 | 5.97 | – | [43] |
| | | 5.0 | 8.82 | 1.76 | |
| | | 7.5 | 9.41 | 1.25 | |
| | | 15.0 | 11.65 | 0.78 | |
| | | 30.0 | 15.94 | 0.53 | |
| Wheat straw ash | Vacuum filtration (0.02 MPa) | 0.0 | 7.99 | – | [43] |
| | | 5.0 | 10.80 | 2.16 | |
| | | 7.5 | 13.07 | 1.74 | |
| | | 15.0 | 14.22 | 0.95 | |
| | | 30.0 | 21.32 | 0.71 | |
| Beech wood ash | Vacuum filtration (0.02 MPa) | 0.0 | 12.18 | – | [43] |
| | | 5.0 | 15.33 | 3.06 | |
| | | 7.5 | 16.59 | 2.21 | |
| | | 15.0 | 20.16 | 1.34 | |
| | | 30.0 | 23.25 | 0.78 | |

conditioned sludge was of about 24–58% higher than for non-conditioned sewage sludge. This explains higher effectiveness of sewage sludge dewatering after previous conditioning by the use of wood ash. Additionally, lower values of CST for dewatered sewage sludge after pressure filtration might suggest that further elimination of water from sludge could be easier in comparison to vacuum pressure [35]. It might be achieved by the increase of pressure or wood ash dosage. Statistical analysis has also shown the statistically high relationship between the final moisture content and CST both for sewage sludge after vacuum and pressure filtration (ANOVA, $R^2 > 0.98$, $p < 0.003$) (Fig. 5).

The addition of wood biomass ashes into sewage sludge resulted in the decrease of total bacteria number (Fig. 6). The main factor that causes the reduction of microorganisms is the elevated pH. For 5, 7.5, 15 and 30 g/dm^3 dosages of ash, the pH of sewage sludge decreased from 6.40 to 7.52; 8.73; 11.65 and 12.51, respectively. The high pH resulted in the mineralization and higienization of sludge [63]. Depending on the amount of wood biomass ash applied in laboratory

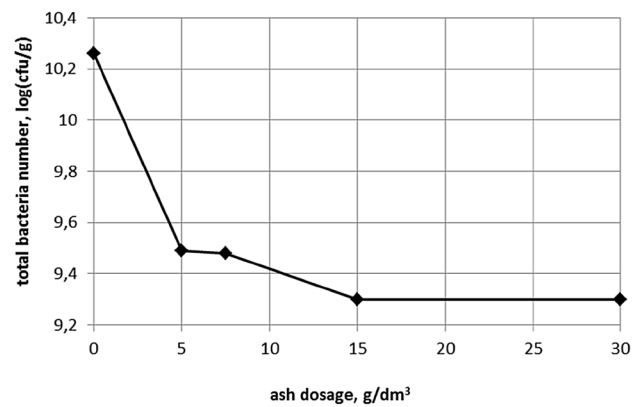


Fig. 6 Influence of biomass ash on the reduction of total bacteria number (laboratory scale)

tests, the total bacteria number decreased by approximately 83–89% in comparison to raw sewage sludge. But Wang and Viraraghavan [64] proved higher effectiveness of other ashes

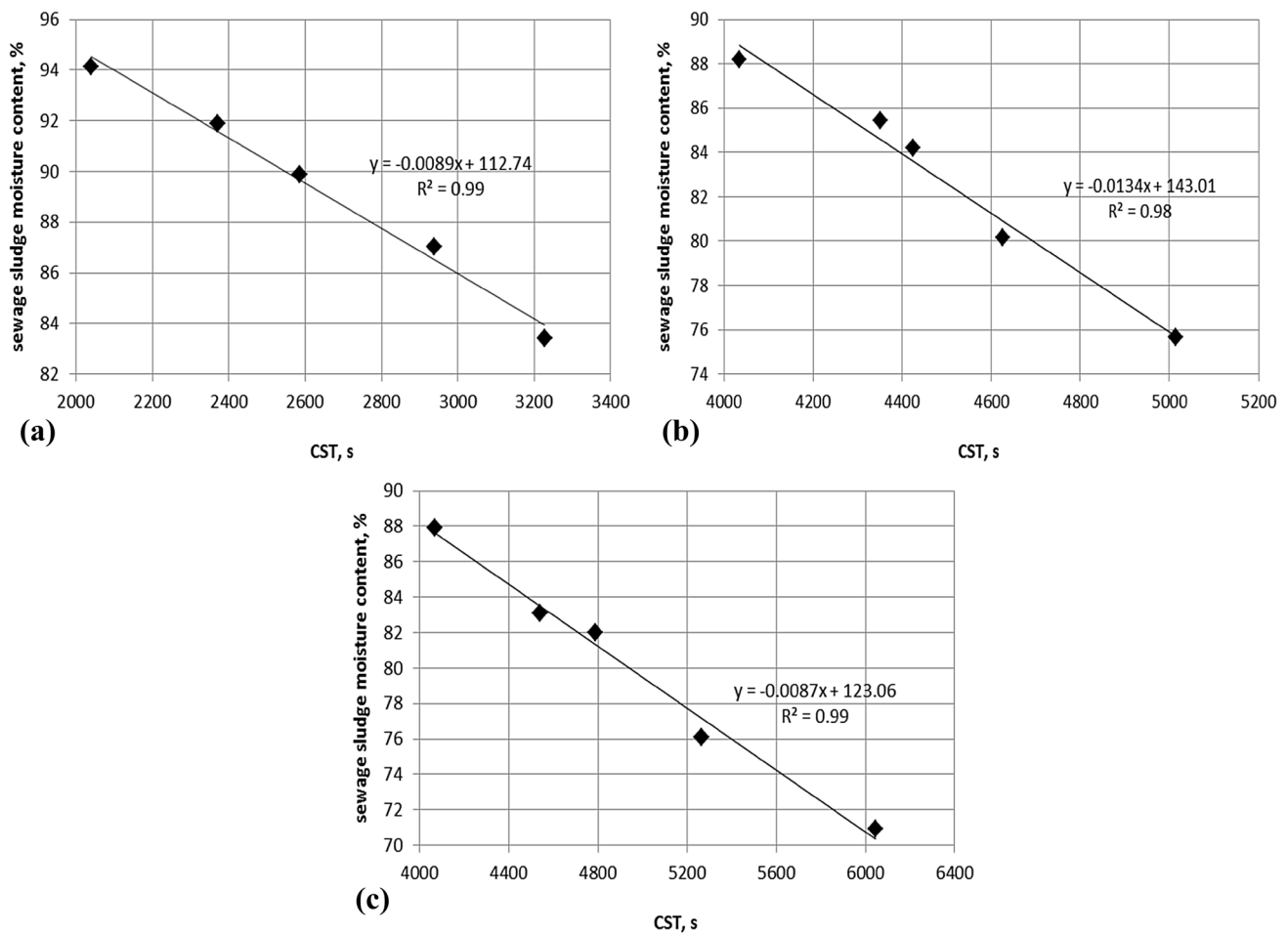


Fig. 5 Statistical relationship between CST and sewage sludge moisture content after pressure filtration (a), after vacuum filtration for the vacuum pressure of 0.01 MPa (b) and after vacuum filtration for the vacuum pressure of 0.02 MPa (c)

in terms of sewage sludge higienization. They achieved even 100% reduction of bacteria in sewage sludge after the addition of coal fly ash in the dosage of 12.6 30 g/dm³ dosages of wood ash. Similar results were achieved by Kincanonn et al. [65] for sewage sludge after conditioning by means of coal fly ash in the dosage of 1 g/g sewage sludge d.m. Wójcik [66] also reported that the addition of willow tree ash in the dosage of 30 g/dm³ can reduce the amount of bacteria in sewage sludge by nearly 70%.

Influence of Wood Biomass Ash on Sewage Sludge Dewatering and Higienisation on a Technical Scale

The results obtained in laboratory tests were verified on a technical scale with the use of a filter belt press. The application of wood biomass ash before sewage sludge dewatering affected the reduction of sludge final hydration. The moisture content for raw sewage sludge after dewatering decreased by only 3%. It confirms the low-dewatering capacity of sludge without previous modification (Table 14). The addition of 15 and 30 g/dm³ of wood biomass ashes resulted in the decline of sludge hydration of approximately 15 and 26%, respectively. The application of the aforementioned materials caused higher effectiveness of sewage sludge dewatering in comparison with the use of polyelectrolyte. Chemical conditioning by means of polyelectrolyte in the value of 0.12 g/dm³ could decrease the final sewage sludge moisture content by about 13%. On the other hand, the sludge moisture content reduction per gram of added wood ash decreased with the increase of the dosage of wood ash.

Similarly to laboratory tests, sewage sludge conditioning by the use of wood biomass ash affects CST after dewatering on a technical scale. Much lower values of the aforementioned parameter were achieved for conditioned sewage sludge (1852 and 3173s) than for raw sludge. However, sewage sludge after chemical conditioning with the use of polyelectrolyte was characterized by the highest value of CST (5181s). It means that sewage sludge containing wood ash is more susceptible to further water elimination in comparison to the dosing of polyelectrolytes.

Figure 7 shows the relationship between the final sewage sludge moisture content and CST. The analysis of the results indicated statistically high relationship between the aforementioned parameters (ANOVA, R² > 0.99, p < 0.001).

The influence of wood biomass ash on microbiological characteristics of the mixture of sewage sludge and ash is presented in Fig. 8. The obtained results proved the positive impact of wood ash on the total number bacteria reduction. But the results were varied depending on the amount of wood ashes applied. For 15 and 30 g/dm³ dosages of wood ash, the total bacteria amount decreased by 40 and 53% in comparison to raw sewage sludge. Also in this case, the reduction of total bacteria count is a result of the increase of pH after the application of wood ash. For 15 and 30 g/dm³ dosages of wood ash, pH of sewage sludge was 11.98 and 12.96, respectively. Due to the high pH, the obtained mixture of sewage sludge and wood ash might contribute to the soil deacidification.

After sewage sludge higienization by the use of lime in the dosage of 0.1 kg/kg d.m., the reduction of pathogens was at the level of 50%. Bazeli [63] showed that the addition of lime in a dosage of 0.1 kg/kg d.m resulted in the 90% reduction of total bacteria count. Lime influences both

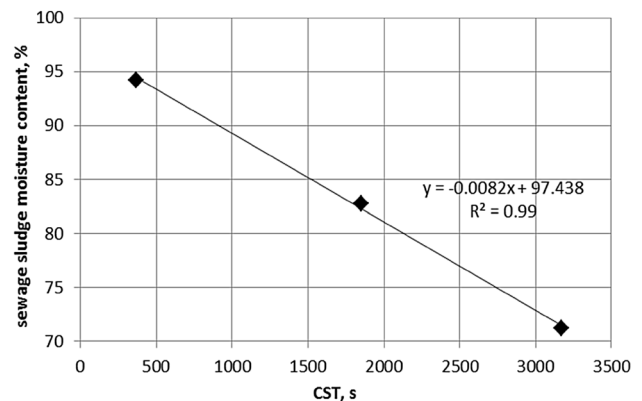


Fig. 7 Statistical relationship between CST and the sewage sludge moisture content after dewatering by the use of filter belt press

Table 14 Influence of wood biomass ash application on sewage sludge dewatering capacity (technical scale)

| Parameter | Unit | Ash dosage [g/dm ³] | | | Polyelectrolyte |
|---|------|---------------------------------|-----------------|-----------------|-----------------|
| | | 0.0 | 15.0 | 30.0 | |
| Initial moisture content | % | 97.29 ± 0.17 | 97.29 ± 0.17 | 97.29 ± 0.17 | 97.29 ± 0.17 |
| Final moisture content | % | 94.23 ± 0.55 | 82.75 ± 1.75 | 71.24 ± 0.28 | 85.28 ± 0.60 |
| Moisture content reduction | % | 3.14 ± 0.47 | 14.95 ± 1.72 | 26.78 ± 0.38 | 12.36 ± 0.66 |
| Moisture content reduction per gram of added wood ash | % | – | 1.00 | 0.89 | – |
| CST | s | 365.57 ± 40.17 | 1851.95 ± 24.39 | 3172.57 ± 28.41 | 5181.04 ± 26.86 |
| CST per gram of added wood ash | s | – | 123 | 106 | – |

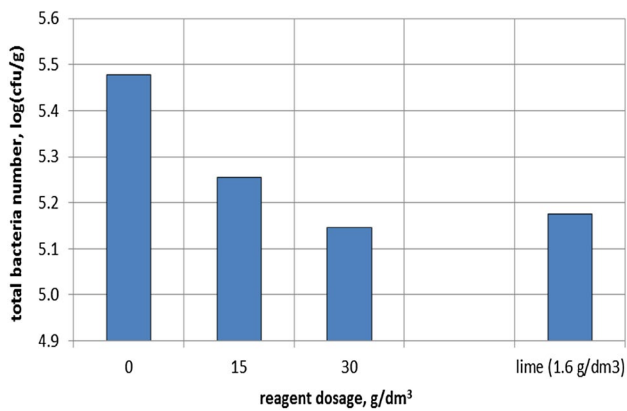


Fig. 8 Influence of wood biomass ash on the reduction of total bacteria number (technical scale)

the increase of temperature and pH of sludge and for this reason; its effectiveness in terms of the sludge higienization might be higher. Wood ashes affect only the increase of pH. But results obtained in this study confirm the advisability of further detailed research concerning the use of energetic waste in sewage sludge treatments.

Discussion

With the increasing number of new residents allocated to the sewerage system, the amount of generated sewage sludge is systematically growing. In compliance with legal and environmental requirements, sewage sludge produced in municipal treatment plants might be properly managed. The prohibition of sewage sludge storage caused the development of other utilization methods, such as combustion, co-combustion and agricultural use. Sewage sludge contains a lot of valuable nutrients and for this reason; its application in agricultural practices is desirable. The use of sewage sludge in agriculture and reclamation is an advantageous treatment due to the deteriorating quality of soil. On the other hand, only chemical and microbiological stable sewage sludge might be applied in agriculture. It implies previous detailed research concerning sewage sludge characteristics before its agricultural application.

The low dewatering capacity and the need to improve water elimination from sewage sludge resulted in the development of conditioning methods. The laboratory tests and research carried out on a technical scale proved high effectiveness of wood biomass ashes in the reduction of sewage sludge moisture content and total bacteria number. Raw sewage sludge has a negative charge and creates a stable system with low dewatering capacity. When the raw sewage sludge was compressed, a highly compressible sludge might deform under pressure. The wood biomass ash acts

as skeleton builder and forms a permeable and rigid lattice structure. Additionally, sewage sludge after conditioning by means of wood biomass ashes remains permeable and porous under high pressure [37, 66, 67]. The addition of wood ash into sewage sludge also contributes to the change of its structure and improves the transport of sludge [60].

The high costs of chemical reagents caused intensive research concerning the use of alternative substances in sewage sludge processing. From the economic point of view, the main advantage of the application of wood biomass ashes in sewage sludge management is the reduction of operational costs of treatment plants. The previous economic analysis of different authors showed the application of filter aids can reduce the cost of sewage sludge dewatering in treatment plants. Ashes are inexpensive and easily-obtained material. The estimated cost of sewage sludge dewatering with the use of coal fly ash was presented by Wang and Viraraghavan [64]. The previous economic analysis was performed for a treatment plant with a capacity of 378 000 m³/d. The analysis of results showed that the application of coal fly ash can reduce the cost of sludge dewatering by 77% in comparison to the sludge conditioning with the use of FeCl₃ and by 62% in comparison to dual conditioning by means of CaO and fly ash [64]. Other economic analysis was carried out by Stachowicz et al. [68] for a treatment plant with a capacity of approximately 2000 m³/d. It was noted that physical conditioning with the use of wood ash can decrease the annual cost of sludge dewatering by approximately 87% in comparison to cationic polyacrylamide. But the initial economic analysis included only the cost of reagents. On the other hand, in order to achieve desirable improvement of sewage sludge dewatering, high dosages of wood ashes are often required. Very high dosages of skeleton builders can increase sludge weight, which influence the subsequent sludge transportation and disposal [60].

Due to the presence of nutrients both in sewage sludge and wood ash, the obtained mixture might be used in agriculture. The chemical characteristic of the mixture of sewage sludge and wood ash was presented in Table 15. The mixture was characterized by the high content of calcium and zinc. In comparison to sewage sludge, the higher concentration of Ca, Mg and Zn was noted in the mixture. Similar observations concerning the content of nutrients in a mixture of sludge and wood ash were noted by Kiper [69]. The addition of wood ash into sewage sludge did not also influence the growth of the content of heavy metals in the aforementioned mixture.

In comparison to manure, the mixture of sewage sludge and wood ash is characterized by the higher content of nutrients. But the concentration of heavy metals in the mixture is also higher than for manure. The analysis of obtained results did not also show the content of heavy metals did not exceed the limited values for sewage sludge which can be applied in

Table 15 Chemical composition of the mixture of sewage sludge and wood ash

| Parameter | Unit | The mixture of sewage sludge and wood ash in a dosage of 30 g/dm ³ | The mixture of sewage sludge and wood ash [69] | Manure [70–72] | Limited values for organic and organic-mineral fertilizers according to [59, 73] |
|-----------|------------|---|--|----------------|--|
| pH | – | 12.96 ± 0.21 | 10.32 | 7.0–7.5 | – |
| Total N | % d.m. | 3.82 ± 0.29 | 40.96 | 0.47–2.30 | – |
| Total P | % d.m. | 1.36 ± 0.11 | 2.89 | 0.05–1.20 | – |
| K | % d.m. | 5.21 ± 0.18 | 149.99 | 0.38–2.03 | – |
| Ca | % d.m. | 26.83 ± 0.23 | – | 0.19–1.19 | – |
| Mg | % d.m. | 0.71 ± 0.08 | 14.91 | 0.05–0.50 | – |
| Zn | mg/kg d.m. | 615 ± 9.45 | 2368 | 150–427 | – |
| Pb | mg/kg d.m. | 10.58 ± 0.14 | 14.42 | – | 140 |
| Cu | mg/kg d.m. | 100.43 ± 3.28 | 338.9 | – | – |
| Ni | mg/kg d.m. | 8.52 ± 0.15 | 20 | 3.0–12.7 | 60 |
| Cd | mg/kg d.m. | 1.61 ± 0.11 | 3.64 | – | 5 |

agriculture. The mixture of sewage sludge and wood ash also meets requirements concerning the concentration of heavy metals for mineral and organic-mineral fertilizers which are contained in the Act of 10 July 2007 on Fertilizers and Fertilization [59]. For this reason, the final product of sludge dewatering might be used in agricultural practices without negative effect on the soil quality.

The application of final product of sludge dewatering is a very important step in a circular economy and recycling. Both sewage sludge and wood biomass ashes supply a lot of valuable nutrients, such as Ca, Mg, K and microelements, which might affect the growth and yield of crops. Due to the non-consumption of biomass, the use of the aforementioned mixture in energetic plant plantations is desirable. The application of sewage sludge containing wood biomass ash in agriculture enables to transform two problematic kind of waste into valuable fertilizer (Fig. 9). Additionally, the potential risk associated with the influence of heavy metals on humans is reduced significantly. The fertilizing of energetic plants might be successfully supported or even replaced by a mixture of sewage sludge and wood biomass ash.

Summary

In this paper, the influence of wood biomass ash on the effectiveness of sewage sludge dewatering was determined. The application of wood ash resulted in the decrease of sewage sludge moisture content and the increase of reduction of total bacteria number, depending on the dosage of ash. The sewage sludge moisture content decreased with the increase of a dosage of wood biomass ash. The best results were achieved for the highest tested dosage of wood ash (30 g/dm³), for which the hydration decreased by approximately 10–23%, depending on the dewatering technique. For 30 g/dm³, the total bacteria count in sewage sludge decreased by nearly 90%. The results obtained in a laboratory scale were also verified on a technical scale with the use of filter belt press. The application of 30 g/dm³ dosage of wood ash caused the decrease of sludge moisture content by 27%. On a technical scale, the total bacteria count decreased by approximately 53%.

The obtained results confirmed the effectiveness of sludge conditioning with the use of wood biomass ashes. Due to the content of nutrients for plants, the final product of sludge dewatering might be considered as a natural fertilizer in perennial plants plantations. Further research will focus on the determination of the influence of the mixture on the crops growth and yield.

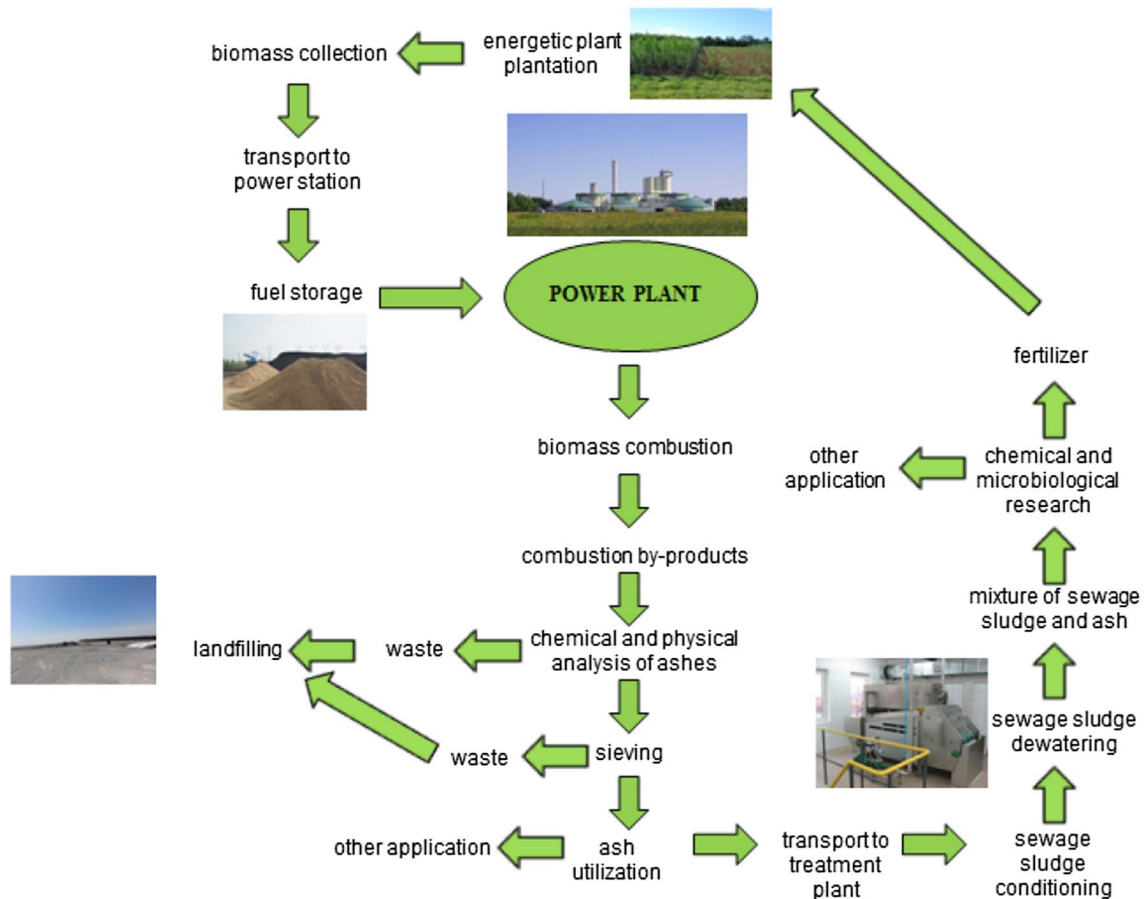


Fig. 9 Closed circuit of the application of mixture of sewage sludge and wood ash

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