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Sustainable Use of Biochar, Poultry and Cattle Manure for the Production of Organic Granular Fertilizers

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Abstract: In agricultural activities, there is an increasing need for organic fertilizers to use nature-friendly materials used to fertilize the soil. Farmers have been using granular organic fertilizers made from composted or dried manure of cattle, poultry, pigs, ash, bone meal, and other materials for some time, but the quantities of these organic fertilizers are not large. Biochar is also being intensively studied as a material to improve soil quality and plant growth and reduce greenhouse gas emissions from soil. The suitability of cattle manure compost, poultry manure, biochar, and their combinations for granular fertilizers was analyzed in this work. The preparation of biochar for granulation may have differences compared to other organic materials due to the moisture content, fractional composition, bulk density, and other parameters of the granulated material, so this work examines the physical–mechanical and chemical properties of cattle and poultry manure and biochar raw material and the final granulated product. Research has found that the fractional composition of raw materials under investigation manure and biochar was up to 2 mm. The moisture content of the studied raw material varied from 8.97% in the case of poultry manure to 25.11% in the case of cattle manure compost. The lowest moisture content was obtained due to additional drying. The addition of biochar reduces the granule density in investigated cases. Poultry manure granules were the most mechanically stable, with a semi-static stability of 382.6 ± 78.08 N. After the addition of biochar, weaker binding properties were determined in the experimental granules. Analysis of the composition of elements shows that these granules can be used for fertilization or soil improvement. High concentrations of nitrogen (N), phosphorus (P), and potassium (K) were detected in the granules. The obtained results showed that it is appropriate to enrich the manure granules with biochar.

Keywords: granular fertilizers; physical–mechanical properties; chemical composition; biochar; manure

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1. Introduction

Currently, organic waste and waste usage as secondary raw materials is an important economic and environmental problem. According to scientific research, 50 million cubic meters of wood waste are produced in the European Union every year [1,2]. In 2015 the adopted circular economy plan aims to orient the economy of European countries towards a more sustainable economy and promote the sustainable economic growth of European countries. This aims to close the life cycle of products and materials, maintaining their value in the economy, and where possible, minimizing the generation of waste, maximizing recycling, and reuse, beneficial to both the environment and the economy [3].

Only about 50% of the wood is produced into useful products, the other 50% turns into waste [4,5]. About half of the generated waste is discarded as damaged residues, followed by tops and branches (33.75%), stumps (10%), unusable logs (3.75%), and scraps (2.5%) [5,6]. The previously mentioned collecting and transporting logging waste to a disposal site is a key issue because the conditions of road and terrain are usually very difficult and sometimes are considered unusable. Collecting and transporting logging waste (stumps, branches, and broken trees) to a disposal site is a main problem because the terrain and road conditions are usually very difficult and are considered unusable [7]. The recycling of wood waste can reduce environmental pollution as production processes use less materials, water, and energy than using primary raw materials [8].

One of the ways to reuse wood waste is to produce biochar. Biochar is a product obtained during the pyrolysis of biological residues at high temperatures in the absence of oxygen [9–13]. Biochar is rich in carbon. It can be produced from various types of organic materials, including agricultural biomass, sewage sediment, forest waste, energy crops, and residues from agro-food processing [14]. Biochar has existed for many years and in recent times it has gained new interest. There is a growing number of studies and research emphasizing the benefits of biochar in environmental protection, agriculture, and waste management [15].

Until now, the charcoal produced during the pyrolysis process has mainly been used as fuel. However, the potential uses of wood charcoal are wider and have higher added value, such as soil amendment materials, activated carbon, electrode materials and graphene [7]. Biochar contains valuable macro- and micronutrients [11]. Adding biochar to the soil increases the absorbed nutrients and prevents them from leaching out, stimulates the activity of important soil microorganisms, and acts as a carbon dioxide absorber. Biochar reduces greenhouse gas emissions and the harmful effects of agrochemicals and locks atmospheric CO_2 in the soil [12,13]. Therefore, biochar can improve soil fertility and plant growth due to its unique properties–water and nutrient retention capacity, and soil enzyme activity [11].

Biochar can be called a stabilized soil additive, especially useful in restoring soil organic matter, improving water retention and soil structure, and providing assimilable nutrients that are necessary for growing plants [11,16]. This can be considered as the utility of biochar properties in solving crop and livestock problems [11].

Biochar has become an old, rediscovered material, successfully gaining popularity not only in agriculture but also in environmental protection. Today, biochar is already adopted as an additive to slurry or compost.

Various waste biomasses provide abundant sources of biochar materials. Due to its porous structure, high surface area, and other properties, biochar is used to absorb phosphorus. Such use has great prospects, although the use of biochar as a slow-release fertilizer is in the research phase [17]. Granulation is an effective option to decrease biochar loss because when spreading loose and dusty products and handling costs for soil application, and realizes practical large-scale application in agricultural practices. Current scientific research results show that applying biochar-based fertilizers is a viable way of promoting sustainable agriculture [18].

The effects of biochar and other organic additives on improving soil quality and plant productivity are evident, especially in degraded or contaminated soils [11,19]. Biochar and manure retain nutrients and can stabilize inorganic pollutants [11,17,20,21]. The use of biochar can improve plant growth and yield, especially when biochar is added to the soil with different kinds of fertilizers [13,22,23]. Biochar effectively traps NH_3, NH_4^+, and NO_3^- in manure [13].

Liu et al. found that enriching the soil with chicken manure and biochar or their combination had positive effects on maize growth, antioxidant, and soil enzyme activity. Furthermore, it is an efficient way to remediate Pb-contaminated soil and improve growing plants [11].

While there is growing research showing the benefits of biochar addition to soil quality, plant growth and yield, agronomic diseases, pollutant removal, and greenhouse gas reduction, there are certain limitations for biochar gaining wider adoption. According to the literature, the benefits of applying biochar to the soil environment can have certain limitations. Our research aims to expand the possibilities of using biochar to improve organic granular fertilizers properties. The innovation of the research is to combine biochar, which is obtained from oak stumps, as logging waste, and manure, as agricultural waste, to produce granular fertilizers. Therefore, the purpose of the article was to create granular cylindrical fertilizers of the most suitable composition of biochar and manure and to study their physical–mechanical, and chemical properties.

2. Materials and Methods

Experimental investigations of cattle manure, poultry manure, and biochar raw material preparation and conversion into granular fertilizers, of physical-mechanical properties were performed, in 2022, in laboratories based at the Department of Agricultural Engineering and Safety of Vytautas Magnus University Agriculture Academy in Lithuania.

Chemical composition research on granular organic fertilizers was performed in the Agrochemical Research Laboratory of the Lithuanian Agricultural and Forest Science Center according to the standard methodology; the main standards are indicated in the text.

Raw material preparation. Biochar was obtained from the grill charcoal production company in the Ukmerge district (Lithuania), which was made from oak stumps. The necessary material (stumps) for the planned research obtained after the city management works, as it is being carried out, and delivered to the charcoal production company. The stumps were crushed into pieces, and mechanically cleaned from the earth and stones remaining between the smaller stump roots. The prepared raw material was placed in a coal kiln–pyrolysis device UMT-3 PLUS EcoTeploOtbor (Ukraine). The mass that did not meet the quality parameters (fraction up to 1 mm) for grill charcoal production was used for mixing with manure material in laboratory conditions with the intention of using it for the production of granules.

The cattle manure compost (approximately 10 kg) was purchased from an enterprise which composts cattle manure in the Kaisiadoriai district (Lithuania).

The poultry manure was purchased from an industrial poultry company in the Kaisiadoriai district (Lithuania). A total of about 10 kg of 3-day-old laying hens manure samples were collected from a mechanized manure removal line from the poultry farm. To achieve a moisture content of about 15% (according to granulator ZLSP200B (Poland) producer manual instructions recommendations), the manure samples were artificially dried in a ventilation canal with a slow flow of heated air under laboratory conditions. Next, the prepared dry raw material was ground, using a hammer mill GMM-1 (Lithuania), to a fine fraction (it was used 2 mm sieve in hammer mill).

Cattle manure samples were purchased from a manure composting company in the Kaisiadoriai district (Lithuania). Biochar and cattle manure compost were not additionally dried or milled.

The experimental scheme of cattle, poultry manure, and biochar mixture fertilizers production shown in Figure 1. The samples were mixed manually, with the aim of achieving a homogeneous mass.

Fractional composition. The fractional composition of milled poultry manure, cattle manure compost, and biochar was determined using a sieve shaker Retsch AS 200 (Haan, Germany) with a set of 200 mm diameter sieves. Holes diameter in the sieves range was 0 mm, 0.1 mm, 0.25 mm, 0.5 mm, 0.63 mm, 1 mm, and 2 mm. There was sieving a 100 g. mass sample of each raw material type, a set of sieves on horizontal surface turned in a semicircle for 1 min. The mass remaining on sieves was weighed using Kern ABJ (Balingen, Germany) scales (accuracy to 0.01 g). The sample part of every fraction in percentage was calculated. Each test was repeated 3 times.

Material bulk density. Bulk density was determined according to the standard methodology (according to EN 1237:2002). Milled material of poultry, cattle manure, and biochar was filled up in the 6 dm^3 cylinders. The empty vessel and vessel with milled material is weighted using Kern ABJ (Germany) scales (accuracy to 0.01 g) and the mass of the mill was calculated. Bulk density is calculated by dividing the mass by the container volume. Each test was repeated 3 times.

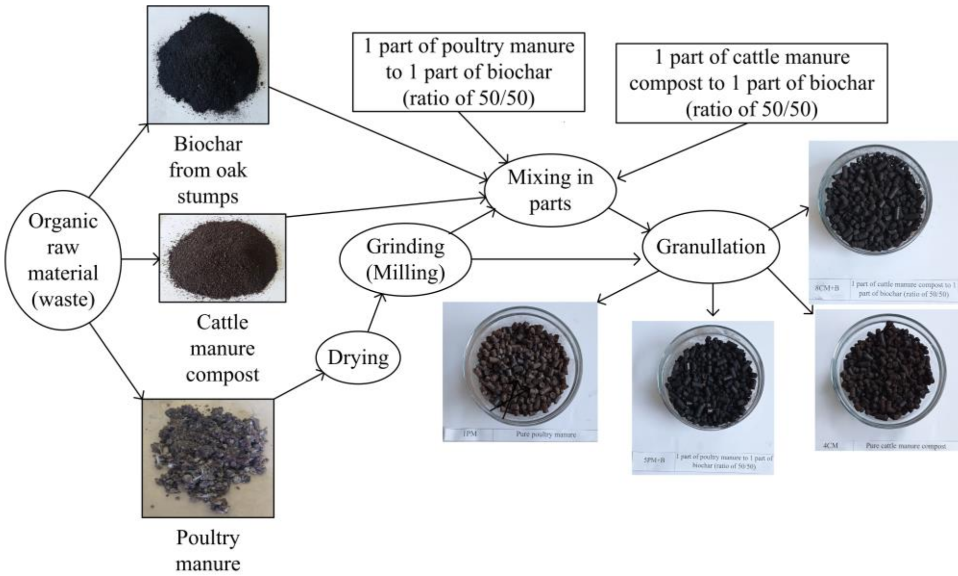

Figure 1. Experimental scheme of cattle, poultry manure, and biochar mixture fertilizers production.

Moisture content. Moisture content was determined according to the standard methodology (according to EN 12048:1999). The initial weight and the weight after drying in a laboratory-drying chamber at the temperature of 105 °C for 24 h were determined.

Granule production. There were four variants of manure and biochar granules produced in laboratory conditions. For granules production was used 7.5 kW granulator with a horizontal granulator matrix (holes of 6 mm diameter) ZLSP200B (Poland). Raw material samples moistened by spraying them with water so that the granulated material acquires surface moisture. All conditions were repeated according to previous experiments [24,25]. Poultry manure, cattle manure compost, and biochar raw material were mixed thoroughly manually of 1.5 kg each to achieve homogeneity. Pure poultry manure (100%) granules were named with code 1 PM. Pure cattle manure compost (100%) was named 4CM. Poultry manure and biochar mixture (1 part of dried poultry manure to 1 part of biochar (weight to weight ratio of 50/50 in percent) named with code 5 PM + B. Cattle manure compost and biochar mixture (1 part of cattle manure compost to 1 part of biochar (ratio of 50/50) named with code 8CM + B.

The granules parameters. Vernier digital caliper LIMIT (PRC) 150 mm (accuracy to 0.01 mm) used for granules height and diameter determination. Granule weight measured by Kern ABJ (Balingen, Germany) scales (accuracy to 0.01 g). Ten granules of each type of sample to obtain the average error were randomly selected to determine the height, diameter, and weights of the granules. The density of investigated granule samples was calculated according to ISO 18847:2016 standard [26].

Granules strength determination. Granules strength tests were performed in a 5 kN capacity test machine "Instron 5960" (USA) and the parameter registration software system "Bluehill". The diameter and height of each cylindrical granule were measured before testing and the granule with a height-to-diameter ratio greater than 2:1 was selected for testing. The granules were placed horizontally on the center of the circular plate and individually compressed until breakage was achieved. Granule compressive strength (N) was determined as the maximum force recorded when compressing the granule at fracture. At that moment, the limiting force (load, N) and extension (deformation, mm) were recorded. This test was performed by compressing the granule with a 9.7 mm die at a speed 20 mm·min^{-1} used. Such a load is considered as semi-static since the effect of inertia is insignificant. Tests were repeated 5 times for each type of granule. The analysis provides significant value in regard to material handling, as granules need a desired amount of strength to survive the remainder of processing and transportation.

Statistical analysis. MS Office Excel was used for the statistical processing of the results. During all data processing using the appropriate number of repetitions, average values, and mean values with the 95% confidence interval of the mean and the least significant difference LSD_{05} was calculated using a t-test at a probability $p \leq 0.05$ [27].

The elementary composition of granules. The pH of the experimental granules was determined according to standard EN 13037:1999 "Soil improvers and growing media–Determination of pH". The dry material was determined according to standard EN 13040:2007 "Soil improvers and growing media". Organic matter was determined according to standard EN 13039:1999 "Soil improvers and growing media–Determination of organic matter content and ash". The elementary composition was determined according to the standards. Nitrogen (N) according to EN 13654-1:2001 "Soil improvers and growing media. Determination of nitrogen Modified Kjeldahl method"; ISO 11261:1995 "Soil quality—Determination of total nitrogen—Modified Kjeldahl method". Phosphorus (P), Potassium (K), Cadmium (Cd), Chrome (Cr), Nickel (Ni), Lead (Pb), Copper (Cu), Zinc (Zn) according to EN 13650:2006 "Soil improvers and growing media. Extraction of aqua regia soluble elements". Organic carbon (C) was determined according to ISO 10694:1995 "Soil quality—Determination of organic and total carbon after dry combustion (elementary analysis)".

3. Results and Discussion

3.1. Determination of Raw Material Physical–Mechanical Properties

3.1.1. Fractional Composition

The fraction composition of dried poultry manure, composted cattle manure, and biochar mass was determined using sieves with holes of various diameters. Manure and biochar fractional composition (%) dependence on sieves holes diameter (mm) is shown in Table 1. Having evaluated the fraction composition of dried and milled poultry manure raw material, we may see that the highest fraction of poultry manure accumulated on a sieve with holes till 0.1 mm diameter (26.26 ± 2.85%), which are in the smallest fraction near dust, and high amount of fraction accumulated on a sieve with holes 0.5 mm diameter (21.71 ± 2.57%). Cattle manure compost contained the most material (36.30 ± 7.28%) in the mass fraction up to 1.0 mm. The character of biochar dispersion on a sieve is more similar to cattle manure compost, big amount of biochar fraction accumulated on a sieve with round holes to 2 mm diameter 42.10 ± 3.91% of the mass. The smallest quantity of dust (to 0.1 mm) was obtained when sieving biochar, only 4.76 ± 3.87%.

Table 1. Average fraction of poultry, cattle manure, and biochar raw material mill remaining on a sieve with error, %.

Type of Raw Material	Diameter Range of Sieve Holes, mm						
	0.0–0.1	0–0.25	0.25–0.5	0.5–0.63	0.63–1.0	1.0–2.0	>2.0
Poultry manure	26.26 ± 2.85	14.22 ± 0.59	21.71 ± 2.57	8.90 ± 0.50	12.22 ± 1.00	13.54 ± 2.76	3.15 ± 3.20
Cattle manure compost	5.07 ± 3.80	15.67 ± 5.41	10.37 ± 3.28	23.33 ± 4.28	36.30 ± 7.28	6.65 ± 4.81	2.61 ± 1.78
Biochar	4.76 ± 3.87	10.31 ± 3.77	13.37 ± 1.76	8.21 ± 2.60	12.43 ± 6.73	42.10 ± 3.91	8.83 ± 1.96

The fractional composition of all types of raw material was in most cases up to 2 mm, so it argued that the dried manure or composted (in cattle manure case) material of all studied types was suitable for granulation. No particles were found of the fraction on a sieve with holes more than 2.0 mm diameter in all raw material variants.

3.1.2. Material Bulk Density, Moisture Content

Poultry manure samples were 70.31 ± 7.58% initial moisture content. Moisture content is one of the dominant factors affecting the granulation process. After artificial drying (about 24 h) of poultry manure samples in a ventilation canal with slow heated air and milling, the determined moisture content was 8.97 ± 0.26%. The poultry manure samples were dried for too long, the material may have had moisture content. Also, after assessing the moisture content of biochar (10.47 ± 1.19%), the optimal amount of moisture in the material can be achieved by mixing wetter manure raw material with biochar. Purchased cattle manure compost moisture content was 25.11 ± 1.36% as it mentioned in the methodological section, it was not additionally dried. From the obtained results, we can see that the highest bulk density of the prepared raw material mill was cattle manure compost material 692.73 ± 13.77, and the lowest bulk density of biochar 457.4 ± 11.85. Dried and milled poultry manure bulk density was 635.7 ± 18.66 kg m^{-3}.

3.2. Determination of Granule Physical–Mechanical Properties

3.2.1. The Granules Parameters

The determined biometric and density parameters of granulated organic fertilizer granules are provided in Table 2. In order to use raw material mass for the granulation process, investigated material compressed in cylindrical granules form using a small capacity granulator ZLSP200B (Poland). Produced granulates were in the range of the diameter from 6.04 ± 0.03 mm (in 8CM + B sample case) to 6.10 ± 0.02 (in 1PM case). Granules' average lengths were from 11.07 ± 1.67 mm (in 4CM and 5PM + B sample cases) to 12.11 ± 0.99 mm (in the 1PM case). Average granule weight was from 0.38 ± 0.05 g (in 5PM + B sample case) till 0.45 ± 0.05 (in 1PM case). Granulation of raw material with such a kind of traditional biomass granulator, with a horizontal granulator matrix, we obtained not wide granules length scattering. It may be influenced by adjusting the knife to the minimum clearance installed in the granulator. It should be noted that for biofuel pellets, what is the granulator originally intended for, the knife is adjusted with the aim of obtaining longer pellets as it is seen from the presented in Table 2 granules properties, poultry manure granules (1PM series) have high density respectively 1279.96 ± 62.23 kg m^{-3} and 1186.76 ± 35.52 kg m^{-3} in cattle manure compost case (4CM series). A biochar additive ratio of 50/50 reduces the density of the granules in both cases. It should be noted, that an attempt was made to granulate pure biochar and its mixtures with manure, with a percentage greater than 50%, but it was found that the granules do not form under such conditions with the equipment we have. Adding water as a binder did not help either. Therefore, it was decided to stay at the ratio of 50/50, thus obtaining the maximum amount of biochar in the granule. In the literature, we could not find many scientific studies on the use of biochar and manure for the production of cylindrical granular fertilizers, so we compare our results more with the works of other scientists on manure granules. According to other authors the density values of the swine manure granules produced from dried swine manure by adding 10% of water was 1407.23 kg m^{-3} and by adding 20% of water 1363.04 kg m^{-3}, respectively [28].

Table 2. Biometric properties of experimental granules.

Sample Code	Diameter *d*, mm	Length, *l*, mm	Weight, g	Granules Density, kg m^{-3}
1PM	6.10 ± 0.02	12.11 ± 0.99	0.45 ± 0.05	1279.96 ± 62.23
4CM	5.77 ± 0.07	12.10 ± 1.50	0.38 ± 0.05	1186.76 ± 35.52
5PM + B	6.06 ± 0.04	11.07 ± 1.67	0.38 ± 0.07	1192.49 ± 61.33
8CM + B	6.04 ± 0.03	11.30 ± 1.09	0.38 ± 0.05	1174.89 ± 62.25

General view of produced poultry manure (1PM), cattle manure compost (4CM), poultry manure and biochar (ratio of 50/50) mixture (5PM + B) and cattle manure compost and biochar (ratio of 50/50) mixture (8CM + B) granules presented in Figure 2. Since the same technology was used for the production of organic granules, it monitored, that visually the granules did not differ, except for the intensity of color. It has to be mentioned, that all tested granule types have no characteristic smell of manure.

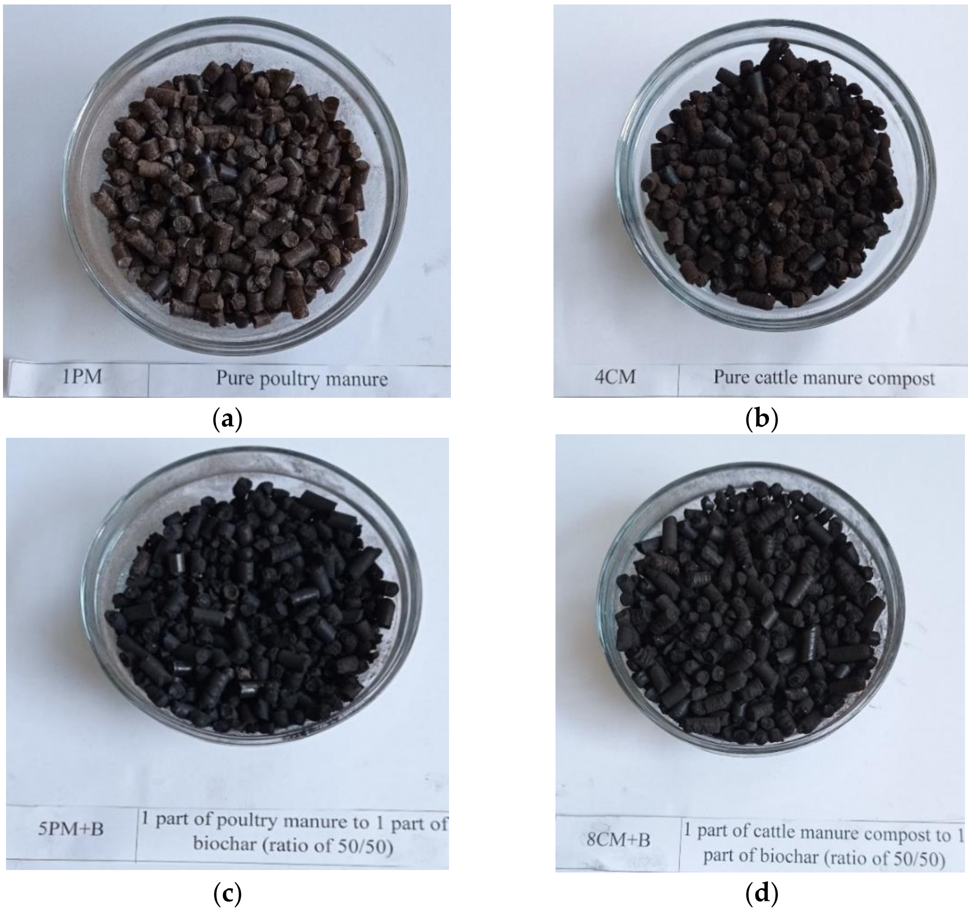

Figure 2. The main view of granules (**a**) 1PM pure poultry manure; (**b**) 4CM pure cattle manure compost; (**c**) 5PM + B 1 part of poultry manure to 1 part of biochar (ratio of 50/50); (**d**) 8CM + B 1 part of cattle manure compost to 1 part of biochar (ratio of 50/50).

3.2.2. Granules Strength Determination

Granules' strength ensures that fertilizer will arrive at its destination as intended and can be used without breaking down into finer particles. The strength test curves of all investigated types of granules, on purpose, show the character of the force variation in the strength test for each granule series type, shown in Figure 3. Analyzing the deformation curves, observed that the maximum crushing force in the horizontal direction was more than 440 N, with deformation ranging from 0.15 mm to 0.4 mm until the granules completely disintegrated in the 1PM granule series (in the five-sample case) and the mentioned granule series showed the greatest strength result. Cattle manure compost granules (4CM) deformed at a maximum compression force of more than 370 N, the compression deformation was from 0.2 mm to 0.7 mm. The poultry and cattle manure granules (1PM and 4CM series) did not disintegrate immediately due to their elasticity properties.

The addition of biochar presented weaker binding properties in the other series samples. The 5PM + B series granules deformed at a maximum compressive force of 350 N, the deformation was from 0.1 mm to 0.3 mm. 8CM + B deformed at a maximum compressive force of more than 203 N; the compression deformation was from 0.05 mm to 0.5 mm before the granules disintegrated. It was noticeable that the granules crushed quicker, and the deformation zone started at 0.05 mm (Figure 3).

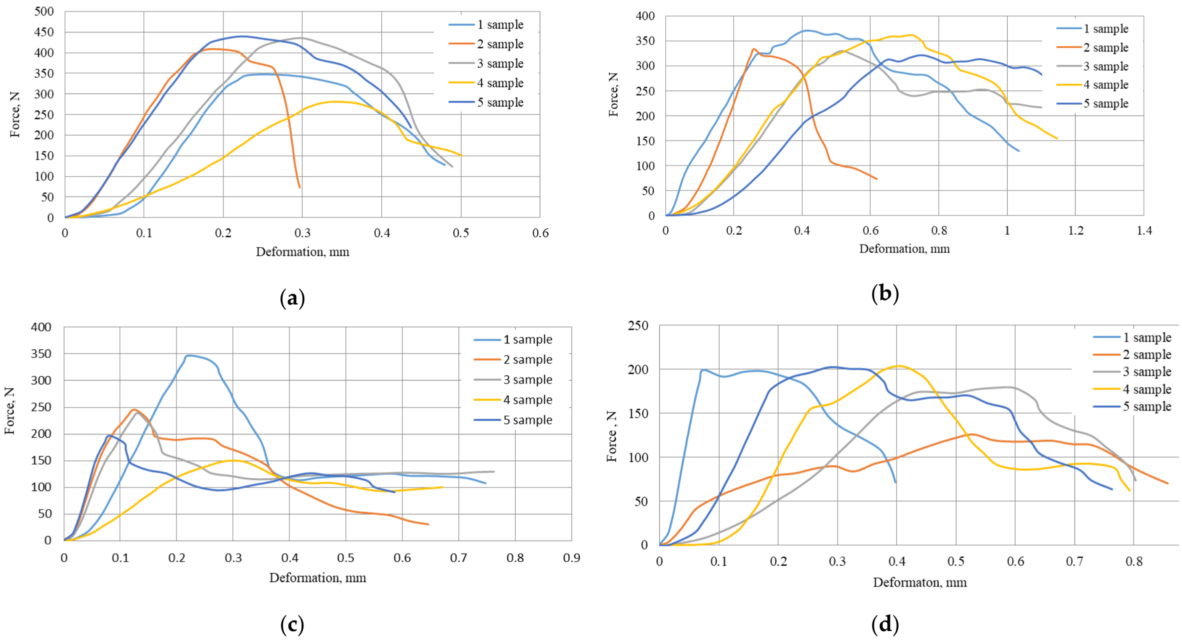

Figure 3. Curves of granules' strength test (**a**) 1PM poultry manure; (**b**) 4CM cattle manure compost; (**c**) 5PM + B 1 part of poultry manure to 1 part of biochar (ratio of 50/50); (**d**) 8CM + B 1 part of cattle manure compost to 1 part of biochar (ratio of 50/50).

The experimental results presented in Figure 4 show that the average strength of the poultry manure granules (1PM series), with a semi-static stability of 382.56 ± 78.08 N in the horizontal direction, was found to be the most mechanically stable. Cattle manure compost granules (4CM) achieved 341.77 ± 26.86 N. There was no significant difference between 1PM and 4CM type granules. Adding biochar presented weaker binding properties in the 5PM + B and 8CM + B series samples. The poultry manure and biochar mixture granules (5PM + B series) showed a semi-static stability of 255.89 ± 63.50 N. The semi-static stability of cattle manure compost and biochar mixture (8CM + B series) granules was 179.57 ± 41.48 N. It is almost two-fold less compared with pure cattle 4CM series granules. The weaker granules are still suitable for use as a granular fertilizer; such granules likely dissolve into the soil easier after receiving moisture, but there is a possibility that granules will break down faster during reloading and storage activity.

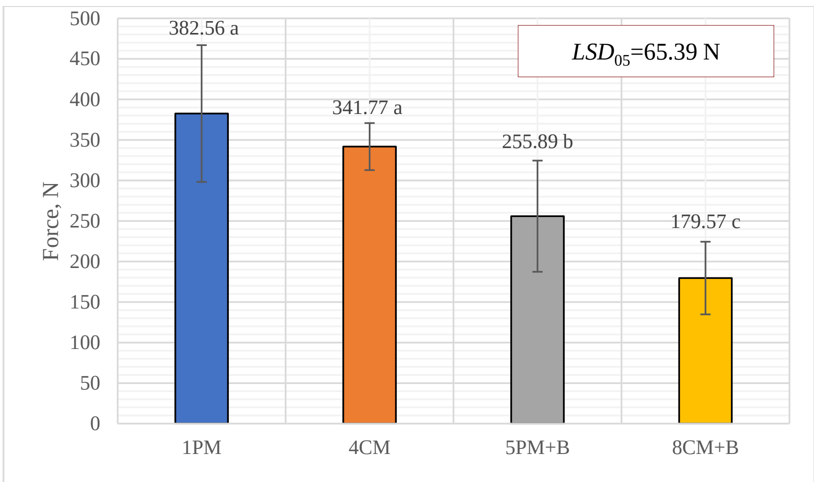

Figure 4. Comparison of the compressive strength of produced organic granules. Matching letters indicate no significant difference between different granules type. Error bars represent the 95% confidence interval of the mean. A *t*-test was used for statistical analysis.

In other experiments, where poultry manure and biomass ash granulation was investigated, granule strength ranged from 140.3 N to 312.6 N [25]. Our investigated granules' strength was quite similar to granules made from composted pig solid fraction with biochar, whose compressive strength was 200–400 N [29]. According to scientists, the mechanical strength of granules made with similar low-capacity ZPL granulators from chicken manure mixed with chopped rye straw varied from 290 to 465 N [30]. According to scientists from Poland, the hardness of granular fertilizers significantly increases together with greater contents of chicken manure and smaller contents of straw. With 80% poultry droppings granules strength achieved 465 N strength [30]. Although the cattle manure compost and biochar (8CM + B) series granules had the lowest compressive strength, they required 179.6 $\pm$ 41.48 N of force to crush the granules. All types of investigated granular fertilizer should be strong enough for storage, operating loads, transportation, and use for fertilizer spreaders without braking. It can be argued that all tested granules were sufficiently strong.

3.2.3. The Elementary Composition of Granules

After performing the research on the physical–mechanical properties of the experimental granules, it was also necessary to perform tests on the chemical composition, with the aim of making sure that the produced fertilizers have nutrients for plants and heavy metals in the composition do not exceed the requirements for fertilizing products.

We performed pure biochar (made from oak stumps) chemical composition research. The analysis showed such results of biochar elementary content: pH was 7.3, Nitrogen (N) 0.0028%; Phosphorus (P) 0.0119%; Potassium (K) 0.0950%. Main heavy metals content: Cadmium (Cd) 0.17 mg kg^{-1}; Zinc (Zn) 86 mg kg^{-1}; Nickel (Ni) 3.13 mg kg^{-1}; Lead (Pb) 8.70 mg kg^{-1}; Copper (Cu) 7.23 mg kg^{-1}; Chrome (Cr) 5.67 mg kg^{-1}. Organic carbon (C) consists of 31.29% of biochar raw material. According to biochar regulations EBC-Agro, the content of heavy metals including lead, cadmium, and mercury must be stated [31]. The use of biochar as fertilizer based on the following limit values to be calculated on the dry matter content (Table 3). In our case, pure biochar raw material met all requirements for heavy metals limits according to European Biochar Certificate (EBC-Agro) [31].

Table 3. Limits of heavy metals for organic fertilizers (in dry material).

Heavy Metals, mg kg^{-1}	Requirements of the Fertilizer Regulation (EU) 2019/1009	EBC-Agro
Cadmium (Cd)	1.0–1.5	1.5
Zinc (Zn)	500–1500	400
Nickel (Ni)	50–60	50
Lead (Pb)	100–120	150
Copper (Cu)	100–600	100
Chrome (Cr)	80–100	90

After the granulation of poultry manure, cattle compost manure, and biochar raw material mixtures we obtained different chemical composition experimental granules. The chemical composition results of experimental granular fertilizers are given in Table 4. The produced experimental product can be treated as a solid organic fertilizer or organic soil improver. According to the Regulations (EU) 2019/1009 of the European Parliament and of the councils laying out rules on fertilizer products (EC) No 1069/2009 and (EC) No 1107/2009 [32], the experimental granules meet the limits in the cases of Cadmium (Cd), Lead (Pb), Zinc (Zn), and other chemical elements. Except in terms of Nickel (Ni) content 80 mg kg^{-1} in the cattle compost manure (1PM), but the mixture (ratio of 50/50) with biochar (in the 8CM + B case) solved the discrepancy and it fits norms and does not exceed 20 mg kg^{-1} (Table 4).

Table 4. Chemical composition of organic tested 1PM, 4CM, 5PM + B, and 8CM + B granular fertilizers.

Test Parameters	Sample Code and Test Results			
	1PM	4CM	5PM + B	8CM + B
pH	8.2	9.9	8.3	9.9
Dry material, %	92.62	78.40	92.29	87.92
In dry matter:				
Nitrogen (N) %	3.11	3.05	2.20	1.57
Phosphorus (P) %	1.76	0.83	1.18	0.55
Potassium (K) %	4.72	6.13	4.23	4.62
Cadmium (Cd) mg kg^{-1}	0.18	0.23	0.29	0.43
Zinc (Zn) mg kg^{-1}	295	115	190	119
Nickel (Ni) mg kg^{-1}	5.97	80.0	5.77	20.0
Lead (Pb) mg kg^{-1}	62.4	3.57	2.57	3.03
Copper (Cu) mg kg^{-1}	50	20.6	80.0	18.0
Chrome (Cr) mg kg^{-1}	7.33	67.0	7.67	22.6
Organic carbon (C), %	22.6	28.7	34.0	31.6
Organic matter, %	65.0	60.8	65.5	47.8

The most important advantage of granular organic fertilizers is that they have 50–75% of organic matter substances. It is a useful tool for restoring humus content in the soil. Granular organic fertilizers available on the European market usually contain 2–4% Nitrogen (N), 1–3% Phosphorus (P), 2–6% Potassium (K), and a small amount of calcium, magnesium, and trace elements. However, nutrients in fertilizers do not dissolve quickly; it takes 1–2 years for them to decompose, depending on meteorological conditions, especially humidity [33]. If organic granular fertilizers are used together with for example mineral fertilizers, plants will use the nutrients contained in the latter more in spring and the first half of summer, and granular organic fertilizers in summer and in the second half of plant vegetation. Depending on the chemical composition, 20–40 kg of Nitrogen (N), 10–30 kg of Phosphorus (P), and 20–40 kg of Potassium (K) are added to the soil with one ton of granular organic fertilizers. Depending on the type of plants, the producers recommend rate of granulated organic fertilizers usually is 1–3 tons per hectare [34]. Nitrogen is important for leaf growth and overall plant health, phosphorus is necessary for root development and fruit production, and potassium is crucial for disease resistance and stress tolerance. According to research results, NPK ratio in experimental granules arranged as follows in the 1PM case 3–1.8–4.7, in 4CM case 3–0.8–6; in the 5PM + B case 2.2–1.2–4.2 and in the 8CM + B case 1.6–0.6–4.6. The addition of biochar reduced the amount of Nitrogen (N) in both variants, especially, almost twice, in cattle manure and biochar mixture (8CM + B sample) granules. Another important parameter is C/N ratio (Carbon to Nitrogen ratio). According to research, the low C/N ratio signifies that the fertilizers readily matured and can provide good mineralization in the form of accessible nitrogen for the plants to uptake and a high C/N ratio will promote nitrogen immobilization, which means that the accessible nitrogen would be taken up by microorganisms preventing the plants from absorbing them [35]. The decomposition of humus depends on the C/N in the organic matter. The more Nitrogen (N), the faster the decomposition of organic matter and vice versa. A C/N ratio of 15–20:1 is required for intensive humus formation. Granulated organic fertilizers are promising fertilizers intended not only for fertilizing plants but also for improving soil properties. The C/N ratio in our research in the 1PM sample case was 7, in the 4CM sample case C/N ratio was 9, in the 5PM + B sample case C/N ratio was 15, and in the 8CM + B sample case C/N ratio was 20. This means that when applied to the soil, these fertilizers in the 8CM + B sample case will intensify humus formation. The addition of biochar significantly increased the C/N ratio, especially in 8CM + B sample case. In our case we obtained quite a low C/N ratio of cattle compost granulated fertilizers, even unexpectedly lower than in the dried poultry manure 4CM sample case.

Further studies are needed to produce more types of manure and biochar granules of different percentage compositions, and use other types of manure in assessing the impact of litter on the mechanical–physical properties of granules, to determine the effects of fertilizers resulting from the production of biochar and manure mixture granules on the Wettability Index (WI). It is also necessary to carry out an analysis of plant growth to verify the feasibility of the fertilizers, the environmental effect, and the costs and benefits of industrial production of such kinds of organic granules.

4. Conclusions

Although many studies have been carried out to substantiate the suitability of organic agricultural waste for granular organic fertilizers, possibilities for preparing manure and biochar mixture for fertilizers production have not yet been analyzed widely. Four types of organic granular fertilizers were produced from cattle manure compost, poultry manure, biochar, and their combinations. The biometric and physical–mechanical properties of all mixtures met the results, which were achieved in other studies. Research has found that the moisture content of the studied raw material varied from 8.97% in the case of poultry manure to 25.11% in the case of cattle manure compost. The lowest moisture content was due to additional drying. The fractional composition of all types of raw material was in most cases up to 2 mm, so it argued that the dried or composted manure and biochar material of all studied types was suitable for granulation. The highest density of produced granules was found in the 1PM and 5PM + B samples (1279.96 ± 62.23 and 1192.49 ± 61.33 kg m^{-3} respectively). Biochar additive reduces the density of the granules in both cases (5PM + B and 8CM + B respectively). Poultry manure granules (1PM series), with semi-static stability of 382.6 ± 78.08 N, were found to be the most mechanically stable. There was no significant difference between the 1PM- and 4CM-type granules. Adding biochar (ratio of 50/50) presented weaker binding properties in the 5PM + B and 8CM + B series samples.

The analysis of the elemental composition and other properties indicates that these granules can be used for soil fertilization or soil improvement. High concentrations of Nitrogen (N) Phosphorus (P), and Potassium (K) were detected in all types of produced granules. The addition of biochar significantly increased the C/N ratio in 8CM + B sample case (C/N ratio 20). When evaluating the content of heavy metals in produced granules, it was found, that their quantities were not large and did not exceed the permissible values, except in terms of Nickel (Ni) content 80 mg kg^{-1} in the cattle compost manure (1PM) granules, but biochar attachment showed a positive influence, reducing the amount of Nickel (Ni) content to permissible values (in 8CM + B case).

In conclusion, the results of this study suggest that the granulation of a manure and biochar mixture using biomass granulators with a horizontal matrix produces granules of high density and granular strength. Arguably, poultry, cattle manure, and biochar materials can be granulated, but better strength results can be achieved with lower amounts of biochar additives.

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