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Doctoral dissertation

Production and use of organic soil enhancers and growing media from agro-residues

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Częstochowa, 2022

APPRECIATIONS

I am grateful for the support during the writing of the dissertation and for the assistance throughout my research career and special gratitude goes to the promotors: dr hab. inż. Krystyna Malińska, prof. PCz and prof. dr ir. Erik Meers. I also wish to thank dr Ana Robles-Aguilar for her support and advice. They have given me the opportunity to start a joint PhD program between the Częstochowa University of Technology and the University of Gent in the frame of the H2020 project: “Nutri2Cycle".

I would also like to thank the members of the Faculty of Infrastructure and Environment at Częstochowa University of Technology for their help and kind words during my doctoral studies.

CONTENTS

Abstract in English

Since the 20-ties of the last century the researchers worldwide have been working on poultry manure, including the properties, methods of managing and the impact on the natural environment. In particular, the issues related to gaseous emissions from poultry manure and the methods for mitigating these emissions predominated. In the current state of the art the fertilizing properties are known of poultry manure. Poultry manure is mainly used to land spreading on the field, pelletizing, combustion, and energy recovery, and as an additive to animal feed.

Technological advancement has brought to the attention new aspects related to safe and efficient management of poultry manure such as the emerging pollutants identified in poultry manure (e.g., pharmaceuticals, pesticides or microplastics) and new methods for processing of poultry manure (e.g., to biochar in the process of pyrolysis) with other applications, including soil fertilization. In addition, the introduction of the harmonized fertilizing regulation in the European Union (EU 2018/1009 from July 16th, 2022; referred to as the Fertilizing Product Regulation) is expected to facilitate production of new fertilizing products from organic by-products and organic waste from agriculture and food processing. The revised and harmonized fertilizing regulations will facilitate the introduction of fertilizing products from organic waste into the market of the European Union.

The presented doctoral dissertation addresses the problem related to the management of poultry manure and potentials for poultry manure based fertilizing products which can be used for fertilizing soil depleted of e.g., organic matter. The scope of the work included: (1) the analysis of the current state of the art through the literature review, (2) the analysis of the properties of poultry manure sampled from a cage breeding system, (3) laboratory processing of poultry manure through drying, pyrolyzing and composting, (4) the analysis of the properties of the obtained materials intended for soil fertilizing, (5) the analysis of C, N and P cycles during composting of poultry manure and (6) the analysis of the effects of the obtained soil enhancers on the soil properties and plant growth.

In this dissertation special attention was paid to the analysis of biochar from poultry manure pyrolyzed at different temperatures and the application of poultry derived biochar for soil fertilization.

The scope of the presented work is in line with the scientific discipline of environmental engineering, mining, and energy. It is expected that the obtained results will advance the state of the art in the area of producing, handling, managing and processing of poultry manure for soil fertilizing.

The presented doctoral dissertation was carried out as a part of the joint PhD program between Częstochowa University of Technology (Politechnika Częstochowska, PCz) and University of Gent in the frame of the H2020 project: "Nutri2Cycle: Transition towards a more carbon and nutrient efficient agriculture in Europe" (Grant Agreement No. 773682, 2018-2023), coordinated by the University of Gent (Belgium).

Keywords: composting, pyrolysis, poultry manure, biochar, fertilizing products, organic soil enhancers, growing media, sustainable agriculture

Abstract in Polish

Naukowcy już od lat 20 ubiegłego wieku nieprzerwanie prowadzą badania nad pomiotem kurzym, jego właściwościami, sposobami zagospodarowania i wpływem na środowisko naturalne. Szczególna uwaga została poświęcona zagadnieniom związanym z emisjami gazowymi ze świeżego pomiotu kurzego oraz sposobami ich ograniczenia. W obecnym stanie wiedzy poznane są właściwości nawozowe pomiotu kurzego. Pomiot kurzy wykorzystywany jest głównie do nawożenia pól uprawnych, granulowania, peletyzacji, spalania i odzysku energii, a także jako dodatek do pasz dla zwierząt.

Wraz z rozwojem technologicznym pojawiły się nowe aspekty związane z bezpiecznym i efektywnym zagospodarowaniem pomiotu kurzego, w szczególności dotyczą one zagrożeń związanych z nowymi zanieczyszczeniami wykrytymi w pomiocie kurzym (np. farmaceutyki, pestycydy, mikroplastik) oraz nowymi sposobami przetwarzania pomiotu kurzego (np. do biowęgla w procesie pirolizy) i związanych z nimi zastosowań, w tym do nawożenia. Dodatkowo, wprowadzenie uaktualnionego prawa o harmonizacji produktów nawozowych na terenie Unii Europejskiej (Regulacja (EU) 2019/1009 z 16 lipca 2022, tzw. Fertilizing Product Directive) jest sprzyjająca i oczekuje się, że zachęci do produkcji nowych produktów na bazie organicznych produktów ubocznych oraz odpadów z rolnictwa oraz przetwórstwa żywności. Uaktualnione prawo nawozowe umożliwia wprowadzenie i obrót produktami nawozowymi otrzymanymi z odpadów organicznych w krajach Unii Europejskiej.

Niniejsza praca doktorska dotyczy problemu zagospodarowania pomiotu kurzego oraz możliwości otrzymywania z niego produktów nawozowych, które mogą znaleźć zastosowanie w uprawie roślin na glebach pozbawionych, np. materii organicznej. Zakres pracy obejmował: (1) analizę stanu wiedzy poprzez studia literaturowe, (2) analizę właściwości pomiotu kurzego z chowu klatkowego, (3) laboratoryjne przetwarzanie pomiotu kurzego w procesach suszenia, pirolizy i kompostowania, (4) analizę właściwości otrzymanych produktów z pomiotu kurzego pod kątem zastosowań do nawożenia gleb, (5) analizę cykli pierwiastków C, N i P podczas laboratoryjnego kompostowania pomiotu kurzego oraz (6) ocenę wpływu otrzymanych polepszaczy glebowych na właściwości gleby oraz na wzrost roślin.

W przedstawionej pracy szczególną uwagę poświęcono analizie właściwości biowęgla z pomiotu kurzego otrzymanego w różnych warunkach temperatury pirolizy oraz jego zastosowaniem do nawożenia gleb.

Tematyka i zakres przedstawionych badań wpisuje się w zakres dyscypliny naukowej: inżynieria środowiska, górnictwo i energetyka. Otrzymane rezultaty w wyniku prowadzonych badań przyczynią się do rozwoju stanu wiedzy w zakresie zagospodarowania pomiotu kurzego w kierunku nawozowym.

Prezentowana rozprawa doktorska została zrealizowana w ramach wspólnego programu doktoranckiego Politechniki Częstochowskiej (PCz) i Uniwersytetu w Gandawie w ramach projektu H2020: „Nutri2Cycle: W kierunku bardziej efektywnego wykorzystania węgla i substancji odżywczych w rolnictwie" (ang. *Transition towards a more carbon and nutrient efficient agriculture in Europe*, (Umowa grantowa nr 773682, 2018-2023), koordynowany przez Uniwersytet w Gandawie (Belgia).

Słowa kluczowe: kompostowanie, piroliza, pomiot kurzy, biowęgiel, organiczne polepszacze gleby, podłoża wzrostowe, zrównoważone rolnictwo

Abstract in Dutch

Sinds de jaren 1920 doen wetenschappers voortdurend onderzoek naar de eigenschappen, beheermethoden en milieu-impact van kippenmest. Bijzondere aandacht werd besteed aan kwesties in verband met gasvormige emissies uit verse kippenmest en de methoden om deze te verminderen. Bij de huidige stand van de kennis zijn de bemestende eigenschappen van kippenmest gekend. Kippenmest wordt gebruikt voor het bemesten van landbouwgrond, granuleren, pelletiseren, verbranden en terugwinnen van energie, maar ook als toevoeging aan veevoer.

Samen met de technologische ontwikkeling verschenen nieuwe aspecten met betrekking tot het veilige en effectieve beheer van kippenmest, met name de risico's die verband houden met nieuwe verontreinigende stoffen die in kippenmest worden gedetecteerd (bijv. geneesmiddelen, pesticiden, microplastics) en nieuwe methoden voor het verwerken van kippenmest (bijv. in biochar via pyrolyse) en aanverwante toepassingen, waaronder bemesting. Daarnaast is de invoering van de geactualiseerde wet op de harmonisatie van bemestingsproducten in de Europese Unie (Verordening (EU) 2019/1009 van 16 juli 2022, de zogenaamde Bemestingsrichtlijn) gunstig en zal naar verwachting de productie van nieuwe producten op basis van organische bijproducten en afval uit de landbouw en voedselverwerking. De geactualiseerde mestwet maakt de introductie en marketing mogelijk van mestproducten die zijn verkregen uit organisch afval in de landen van de Europese Unie.

Dit proefschrift gaat over de problematiek van het beheer van kippenmest en de mogelijkheid om er bemestingsproducten uit te halen die gebruikt kunnen worden bij de teelt van planten op bodems dewelke bijvoorbeeld arm zijn aan organische stof. De omvang van het werk omvatte: (1) analyse van de stand van de kennis door middel van literatuuronderzoek, (2) analyse van de eigenschappen van kippenmest uit de kooihouderij, (3) laboratoriumverwerking van kippenmest in de processen van drogen, pyrolyse en compostering, (4) analyse van de eigenschappen van de verkregen pluimveemestproducten in termen van toepassingen voor bodembemesting, (5) analyse van de kringlopen van elementen C, N en P tijdens laboratoriumcompostering van kippenmest en (6) beoordeling van de impact van de verkregen bodemverbeteraars op bodemeigenschappen en plantengroei.

In het gepresenteerde werk werd bijzondere aandacht besteed aan de analyse van de eigenschappen van biochar uit kippenmest verkregen onder verschillende omstandigheden van pyrolysetemperatuur en het gebruik ervan voor bodembemesting.

Het onderwerp en de reikwijdte van het gepresenteerde onderzoek maakt deel uit van de wetenschappelijke discipline: milieutechniek, mijnbouw en energie. De resultaten van het uitgevoerde onderzoek zullen bijdragen aan het bevorderen van de stand van de kennis op het gebied van beheer van kippenmest richting bemesting.

Het gepresenteerde doctoraatsproefschrift werd uitgevoerd als onderdeel van een gezamenlijk doctoraatsprogramma van de Częstochowa University of Technology (MS) en de Universiteit van Gent als onderdeel van het H2020-project: "Nutri2Cycle: Towards a more efficient use of carbon andnutrients in farming. " landbouw in Europa, (Subsidieovereenkomst nr. 773682, 2018-2023), gecoördineerd door de Universiteit van Gent (België).

Trefwoorden: composteren, pyrolyse, kippenmest, biochar, biologische bodemverbeteraars, groeimedia, duurzame landbouw

List of abbreviations and symbols

CEC – cation exchange capacity, cmol/kg

CH_4 – methane, %

C_{org} – organic carbon, %

EC – electrical conductivity, mS/cm^3

H_2PO_4 – phosphoric acid, %

H_2S – hydrogen sulfide, %

HPO_4^{2-} – hydrogen phosphate anion (V)

MC – moisture content, %

N_2O – dinitrogen oxide, nitrous oxide, %

N-NH_4 – ammonium nitrogen, kg/m^3

NO_3^- – nitrates, %

OM – organic matter, %

P_2O_5 – tetraphosphorus decoxide, available phosphorus, mg/kg

pH – the quantitative scale of acidity and alkalinity of aqueous solutions

PM_{10} – suspended dust with a diameter <10 µm

$PM_{2.5}$ – suspended dust with a diameter <2.5 µm

TOC – total organic carbon, %

I. Introduction

Rapid development of agriculture and constantly increasing demand for food, especially plant-based food, resulted in extensive use of soil which in consequence led to depletion of soil organic matter in many areas. Agriculture and food processing sector generates significant quantities of organic wastes which need to be managed to prevent from losing of valuable nutrients such as C, N and P and to mitigate the pressures on the natural environment. Most of these organic wastes can be processed and use for soil fertilization.

Poultry manure is one of these byproducts from agriculture which can be processed and used as soil enhancer. There are many references in the literature to the use of poultry manure in processes including composting, combustion, methane fermentation, pelletization, and pyrolysis. The interest in exploiting the potential of organic matter from poultry manure is also combined with the search for poultry manure management alternatives. Still, there is a problem with proper handling, managing and efficient processing of the excess of poultry manure. This has been observed mostly in Poland, USA, China, and Brazil which are leading in the global production of poultry.

In Poland, in most of the cases poultry manure is used as a fertilizer for plants. In practice, unprocessed poultry manure is spread on the fields. The use of poultry manure as a soil enhancer processed into compost or biochar were not commonly used in practice. However, since July 16th, 2022 the harmonized regulation on fertilizing products, i.e., Fertilizing Product Directive has been in force on the territory of the entire European Union, Regulation (EU) 2019/1009 of the European Parliament and of the Council of June 5, 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003. The implementation of the Fertilizing Product Directive, which harmonizes fertilizer properties and provides permission for new products, is essential for producers and farmers. Producers will be able to launch new fertilizing products based on organic substrates not only on the domestic market and in the entire European Union. Farmers will have a more extensive choice of assortments that contribute to environmental protection.

Therefore, this harmonized legislation creates more opportunities for processing of poultry manure into added value products which can be used for soil fertilization. Products such as biochar and compost based on poultry manure can be an alternative to raw poultry manure. These products, compared to raw poultry manure, have limited gaseous emissions, especially ammonia and carbon dioxide, are microbiologically stable, have no significant amounts of heavy metals, and have a beneficial effect on the physical and chemical properties of different types of soil.

A comprehensive approach to processing poultry manure for fertilizing purposes is also required for agriculture and the environment, where the concept of sustainable agriculture and circular economy is being promoted. The movement towards more sustainable agriculture and the reuse of agricultural residues to recycle valuable nutrients is important for the worldwide economy, which needs to manage the increasing demand for food with as minimal environmental degradation as possible.

II. Theoretical

1. Organic soil enhancers and growing media

Organic soil enhancers are organic materials that are used to improve soil properties. In general, organic soil enhancers are derived from agricultural residues (i.e., agro-residues) subjected to various biological, chemical, and physical processes (BloomSoil, 2020). Organic soil enhancers are required to be composed of 95% bio-based materials (Regulation (EU) 2019/1009). The use of soil enhancers based on agricultural residues provides the efficient use of agricultural resources that will have a positive impact on the soil and plants. The use of the fertilizing potential of agricultural residues to produce soil enhancers, contributes to reducing the generation and storage of excessive amounts of organic waste. This kind of practice provides an opportunity to use produced soil enhancers as one of the practices of sustainable and circular agriculture (Rizvi et al., 2015; Akram et al., 2016; Ansari et al., 2017a; Ansari et al., 2019). Organic soil enhancers have the effects on soil properties as well as plant growth and yield. These effects depend on the origin, chemical composition, and degradation period of organic soil enhancers. Therefore, there are not any organic soil enhancers which can be universal for the application to all types of soils and plants (Ansari et al., 2019). Inorganic soil enhancers are derived from inorganic materials such as minerals, e.g., keramsite, sand, shale (BloomSoil, 2020).

The 19th century was a crucial time when inorganic fertilizers and significant amounts of pesticides started to be applied, resulting in the displacement of organic fertilizers such as animal manure and green waste (Willer et al., 2010). Consequently, these materials accumulated on the farms and led to the contamination of the soil, water, and air. Pathogens that proliferated in soil contaminated with organic fertilizers demonstrated aggressive activity in relation to the plants that were in the soil. The pathogens caused plant diseases that resulted in the inhibition of proper plant growth (Ansari et al., 2019). From that time, the impact of pesticides and inorganic fertilizers on human health and negative environmental impact began to be considered carefully (Lazarovits, 2001). The focus has been on harnessing the fertilizing potential of organic materials to prevent their excessive storage. This had a beneficial effect on the re-cycling of organic matter in the environment (Ansari et al., 2019).

Growing media are available in solid or liquid form. Growing media, as compared to organic soil enhancers, concentrate more on affecting plant growth through the development of the root system (MaxiumYield, 2018). Growing media are produced by mixing soil and various soil enhancers, such as organic (e.g., compost, peat, plant waste) or inorganic (e.g., vermiculite, perlite, pumice, sand) materials (Ansari et al., 2019). Plants are supplied with nutrients, the growing media become properly aerated and contain a higher water content (MaxiumYield, 2018).

The production of soil enhancers and the use of growing media from recycled organic materials is a beneficial way to reduce the use of chemical fertilizers. Soil enhancers can be obtained by composting, pyrolysis, anaerobic digestion, granulation, drying of materials, and other processes (Ansari et al., 2019). The benefits of using organic soil enhancers and growing media include improved soil physical properties (e.g., increased water sorption, soil aeration and retention of organic matter by soil aggregates) and chemical properties (increased carbon mineralization rate, quicker and higher release of plant-available nitrogen and phosphorus, reduced soil acidity, improved plant growth) (Goss et al., 2013; Ansari et al., 2019). For example, the 30% reduction in bulk density with the application of sewage sludge, has a positive effect on soil aeration and microbial biomass (Bulluck et al., 2002). Bernal et al., (1992) reported the 12% increase in soil water retention when soil enhancers were added.

The addition of soil enhancers assists in the recovery of soil degraded by fertilizers and exhausted after long-term cultivation of a single crop type. For example, the application of cotton residue compost and poultry manure resulted in the 70-80% recovery of soil vegetation compared to the control which achieved only 5% vegetation recovery (Tejada et al., 2006; Goss et al., 2013).

1.1. Types and functions of organic soil enhancers

Depending on the fertilization requirements of the soil, appropriate soil enhancers should be selected. Soil enhancers can be divided into four basic groups (Figure 1.).

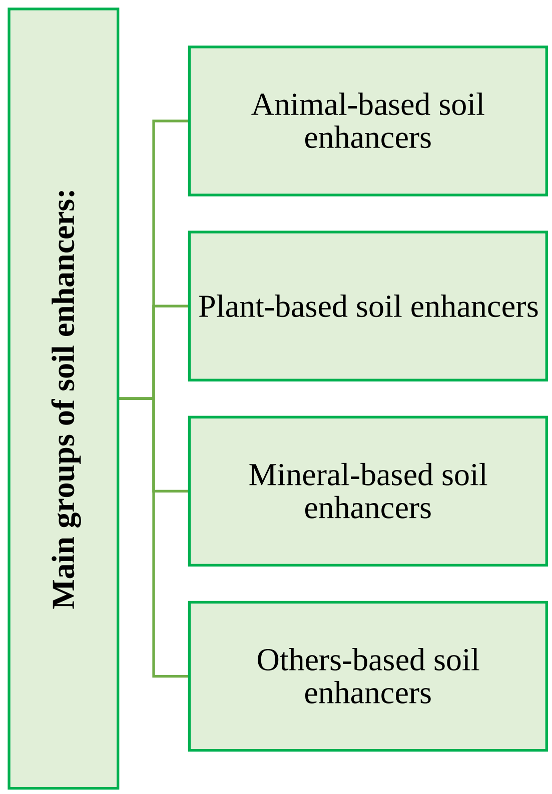

Fig.1. The main groups of soil enhancers (Lowenfels et al., 2010; Tenthacrefarm, 2022).

1.1.1. Animal-based soil enhancers

Most of animal-based soil enhancers are produced from animal manure. However, in the literature it is also possible to find information on the production of soil enhancers based on animal bones. An example is biochar, which is produced by pyrolysis from animal bones, at 600-850°C. Production of biochar from bones, provides soil enhancers that contain almost 30% P_2O_5. Soil enhancers in the form of biochar from bones, can be a replacement for mineral phosphate fertilizers (Terra Humana Ltd., 2017).

However, soil enhancers based on animal manure is a combination of feces, urine, and the substrate (litter) where the animals are residing (Goss et al., 2013). In the European Union and Great Britain, livestock excreted over 1.4 billion tonnes of manure/year (Köninger et al., 2021). To produce soil enhancers, swine manure, cow manure, and poultry manure are most frequently used due to their availability and abundance in agriculture. In table 1 the comparison of animal faeces in the solid and liquid form was prepared in terms of the content of mineral composition.

Tab.1. Comparison of the mineral composition of animal faeces in the solid and liquid form (IUNG, 2000; Beusen et al., 2008; Hjorth et al., 2010; AgroProfil 2019; AgroProfil, 2020).

Parameters	N	P	K	Ca	Na	P_2O_5	K_2O	CaO	Mg
Manure									
Units	kg/t								
Cow	4.7	2.8	6.5	4.3	1.0	2.8	6.5	4.3	1.5
Pig	4.3	4.4	6.8	4.4	1.2	3.3	6.8	4.4	0.8
Horse	5.4	2.9	9.0	4.3	0.6	2.9	9.0	4.3	1.6
Sheep	7.5	3.8	11.9	5.8	1.2	3.8	11.9	5.8	1.9
Poultry	15	15	4.0	28	0.4	15	3.7	28	4.1
Slurry									
Units	kg/m^3								
Cow	3.2-3.4	0.6-1.6	1.5-6.5	0.6-3.2	0.1-1.3	0.3-2.0	3.7-8.0	0.6-2.1	0.4-0.8
Pig	2.8-4.3	0.5-2.0	1.0-3.9	0.7-4.5	0.2-0.8	0.4-3.3	2.3-4.1	0.8-2.5	0.3-0.8

Animal manure consists of feces, urine, and animal litter while slurry consists of fermented urine, a small amount of feces, and water from animal watering and washing places where animals are kept (IUNG, 2000). The composition of the slurry and manure depends on the type of animals, the feed they consume, the water content and the admixture of other liquid fertilizers. Most of the chemical components of slurry are in mineral form which is easier absorbed by plants than from solid animal manure. For root crops, e.g., potatoes, maize, oats and beets, nitrogen from the slurry can cover 100% of their needs for this chemical component. However, the 50% of nitrogen requirements can be covered with animal slurry for winter crops and 25% for canola (AgroProfil, 2019; Ansari et al., 2019).

Animal manure, since the moment of excretion, runs through a variety of dynamic chemical transformations. The main products are NH_4^+, HCO_3^- and OH^-. These compounds affect the pH and the release of NH_3 into the atmosphere (Ansari et al., 2019).

From animal manure, the liquid part of feces can also be separated, i.e., slurry. If the slurry is stored for a long time, the liquid parts of the slurry can separate. The separated layers can have different physicochemical properties. In animal manure and slurry, aerobic and anaerobic reactions occur. Aerobic conditions inhibit the decomposition of carbon dioxide from animal manure. Anaerobic conditions encourage the conversion of carbon compounds to volatile organic acids and the emission of methane (Patni et al., 1987; Ansari et al., 2019).

Proper storage and frequent mixing of animal manure improves microbial activity. This procedure can increase the productivity of microorganisms by up to 5.5 times, which also improves the properties of animal manure as a soil enhancer (Ansari et al., 2019).

1.1.2. Plant-based soil enhancers

Plant biomass waste from agriculture

Green waste comes mainly from agriculture and horticulture. Agricultural waste is dominated by crop residues and straw. More than 700 mln Mg of agricultural waste is generated annually in the EU (Agrocycle, 2019). Plant-based agricultural waste mainly comes from agriculture, horticulture, aquaculture, fishing, forestry, hunting and food processing. To avoid biological and chemical hazards, this waste should be managed in accordance with the environmental management system (The Ministry of Agriculture and Rural Development and the Institute of Technology and Life Sciences in Falenty, 2014; Ansari et al., 2019). Table 2 presents the examples of agricultural waste which have the potential to be used to produce soil enhancers.

Tab.2. Selected micro and macronutrients in the substrates to produce soil enhancers from agricultural waste (Goss et al., 2013; Vandecasteele et al., 2013; Michalak et al., 2016; Lu et al., 2018; Vegan Fertilizer, 2020; Tubeileh et al., 2020).

No.	**Parameters**	**P**	**K**	**Ca**	**Mg**	**Cu**	**Mn**	**Zn**
	Units	$g*kg^{-1}$						
1	Wheat straw	0.6	2.6	2.9	0.7	+*	+	+
2	Corn straw	0.23	1.23	<5	<6	+	+	+
3	Rice straw	0.16-0.27	1.4-2.0	3.5	2.0	+	+	+
4	Maize straw	1.2	12.31	-	-	+	+	+
5	Grass hay	2	17.6	4	1.2	+	+	+
6	Pine-bark	<1	<1	<18	<1.5	<35	<180	<80
7	Coconut fiber	<1	<8	<5	<2	<17	<80	<120
8	Peat	1-2	<2	<5	-	<50	<1150	<60
9	Plant residues	0.44-12.64	4.15-31.54	4-54	1-6	18-23	23-29	70-298
10	Grass hay	1.98	2.6	4.0	1.17	0.03	0.01	0.03
11	Grass clippings	4.10	35.4	4.8	1.71	-	0.01	0.01

+* is present, but the exact content has not been specified.

Green manures are one of the substrates to produced soil enhancers, which are grown in the soil to improve nutrient content. The example is legumes which leave a reserve of N in the soil that would be used to grow the next crop. Examples of this kind of plants are *Sesbania* spp., *Vigna unguiculata, Mucuna pruriens* (Whitbread et al. 2004; Singh et al. 2010; Sugumaran et al., 2016). The application of green manures increases plant biomass production, has a positive effect on soil properties and microorganism communities living in the soil (Ansari et al., 2019).

Food waste

Another group of substrates from which soil enhancers can be produced is food waste. According to Caritas Poland in 2021, approximately 9 million tons of food were wasted in Poland. The 50% of this comes from households and the other half from stores that have not been able to sell food products or other facilities that handle food. The most frequently thrown-away food products are fruits and vegetables. These products are thrown away because of expiration dates, buying excessive amounts of food and buying low-quality products (Climate, 2021).

Globally, 17% of the food produced in 2021 was wasted. Of this, nearly 43% came from households, 26% from gastronomy and 13% from retail (UNEP Food Waste Index Report, 2021). According to FAO (2013) and Barerra et al., (2021), there is a noticeable pattern between food waste and income. Middle- and high-income regions are more exposed to food waste in the consumer phase. In comparison, the lower-income, developing regions are more exposed to food loss and waste at the early step due to a lack of or insufficiently advanced harvesting techniques.

Food residues that end up in the landfill generate significant amounts of methane, carbon dioxide and chlorofluorocarbons. Also high is annual greenhouse gas emissions from food waste. For a country with the population is approximately 80 million people, carbon dioxide emissions from vegetable waste are 2.11 Mt CO_2, from fruit waste are 1.39 Mt CO_2, and from cereals are 2.82 Mt CO_2 (Cakar et al., 2020). Thus, contributing to the increase in greenhouse gas emissions and climate change. When food is wasted, there is also a significant loss of water that has been used to produce food. It is estimated that by pouring one glass of milk into the sewage system, almost 1000 liters of water that was used for production of milk are wasted (FAO, 2013).

Food residues from households, food service and retail are mainly managed through anaerobic digestion, co-anaerobic digestion, composting, controlled combustion, storage, garbage/discards, and sewer also used as animal feed (UNEP Food Waste Index Report, 2021). Table 3 presents the examples of food waste and the content of nutrients that can be used in future biological, chemical, and physical processes.

Tab.3. Fertilizing potential of food waste.

No.	**Parameters**	**N**	**P**	**C**	**C/N**	**pH**	**References**
	Units	%			-		
1	Food waste	3.28	0.56	45.5	13.9	4.39	

2	Herb residues	1.62	0.49	48.0	29.6	5.15	Zhou et al., 2018
3	Herb residues	1.55	0.50	47.0	30.3	5.12	
4	Vegetable and gastronomic waste and bread	1.58	+*	42.3	26.7	5.6	Chikae et al., 2006
5	Kitchen residues	2.0-3.0	0.58	31.7-38.5	16.2	+	Zhang et al. 2016
6	Kitchen residues	1.14-1.36	+	37.3	27.4-35.1	4.2-5.8	Yang et al., 2013
7	Food waste from gastronomy	+	0.40	+	17.6-20.8	4.2-5.0	Cakmecelioglu et al., 2005
8	Food waste from gastronomy	2.7	0.47	47.1	17.3	6.1	Shi et al., 2016
9	Potato peel waste	1.3	0.13	53	+	5.5	Arapoglou et al., 2010
10	Peels of bananas	1.1	0.46	41.4	39	5.1	Bardiya et al., 1996
11	Pineapple waste	0.9	0.51	51.9	55	4.9	

+* is present, but the exact content has not been specified.

Food waste demonstrates pH in the range from 4 to 6, are rich in nitrogen compounds, the C/N ratio ranges from 15 to 30, and the dry weight of waste is 20 to 40% (Wang et al., 2018). The physicochemical potential of food waste provides an opportunity to use them as substrates to produce soil enhancers (Muchova and Obreza, 2001; Obreza and O'Connor, 2003; Goss et al., 2013; Galanakis, 2015; Ansari et al., 2019).

Food processing waste

Food processing waste can be used to produce soil enhancers include paper waste, sugar beet processing waste, oilseeds, distilleries, sugarcane, wine industry waste, fruit pomace (Sardar et al. 2013; Dotaniya et al., 2016; Ansari et al., 2019).

Fruit pomace as well as sugarcane and sugar beet wastes are mainly used as animal feed, biomass used for biogas and bioethanol production, dried fruit, pectin extraction, flavors, dyes, citric acid production, and seeds into polishing cloths, fruit and vegetables waste applied directly to crop fields, and as a substrate for soil enhancers (Kruczek et al., 2016). Soil enhancers produced from fruit pomace have positive effects on plant biomass growth. Food processing waste are often mixed with soil or processed through biomethanation and used in agriculture (Dotaniya et al., 2016). Table 4 presents the examples of food processing waste and their nutrient content.

Tab.4. Substrates to produce soil enhancers from food processing.

No.	Parameters	N	C	P	C/N	pH	References
	Units	%			-		
1	Soy waste	5.9	18.8	+*	3.4	7.4	Wong et al., 2001
2	Malt waste	5	48	+	26	+	Winter et al., 1999
3	Hemp waste	0.1	41.6	0.3	21-25	6.1-7.5	
4	Cornstalks	0.1	50	+	19-25	5.5-7.2	
5	Apple pomace	0.7	12.8	+	+	+	Banerjee et al., 2017
6	Waste from spruce wood	0.22	49.3	+	+	+	
7	Tomato pomace	+	4.5	+	+	+	Roy et al., 2016
8	Sawdust	0.12	51.5	0.007	28	5.37-5.49	Gao et al., 2010
9	Tofu residues	2.1	42.3	+	+	5.6	Kim et al., 2011

+* is present, but the exact content has not been specified.

Food processing waste from vegetable and fruit processing is rich in nitrogen, carbon, proteins, fatty acids, minerals, and antioxidant compounds. From the processing of plants in industrial processes, waste is generated in the form of leaves, peels, seeds, bran, and bagasse (Difonzo et al., 2022). Vegetable and fruit residues, after industrial processes in 95% in Poland, are used for further processes and only 0.1% of such waste in Poland is landfilled. Vegetable waste from processing plants is also used as a substrate for composting (Białecka, 2008; Kruczek et al., 2016; Grzelak-Błaszczyk et al., 2021).

1.1.3. Mineral-based soil enhancers

In the literature, mineral-based soil enhancers are called mineral soil conditioners (MSCs). They are used to improve soil acidity and fertilizer quality. MSCs are produced from sinters of limestone, potassium, and dolomite. They are characterized by a rich content of silicon, potassium, calcium, and magnesium (Yang et al., 2020). Table 5 presents the examples of mineral-based soil enhancers.

Tab.5. Mineral-based substrates to produce soil enhancers.

No.	Parameters	CaO	MgO	K_2O	SiO_2	pH	References
	Units	%				-	
1	Olivine	+*	68.1-257.6	16-130.7	+	4.9-5.9	Haque et al., 2019
2	Kieserite	+	15.7-30.6	27.6-55.2	+	4.9-5.0	
3	Basalt	6.8-88.5	32-215.2	50-266.4	+	+	
4	Mineral soil conditioners	32.32	4.80	7.10	40.18	+	Yang et al., 2020
5	Dolomite	+	+	21.80-23.15	+	6.08-6.87	Rastija et al., 2014

6	Pyrite ash	0.44-6.83	0.03	0.1-03	0.65-1.51	+	Oliveira et al., 2012
7	Greensand (composed from glauconite)	-	-	8	-	6.3	Franus et al., 2014

+* is present, but the exact content has not been specified.

The addition of silicon, calcium, sodium, and potassium to the soil increases the content of alkaline cations. This regulates soil pH and stabilizes the physicochemical processes occurring in the soil. Adding mineral-based soil enhancers, improves water retention and loosens the texture of compacted clay soil (Haque et al., 2019; Yang et al., 2020).

1.1.4. Others-based soil enhancers

Sewage sludge

The municipal sewage in liquid and solid form, after proper transformation, can be used as soil enhancers to increase the yield of crops. In Europe, 37% of sewage sludge is used in agriculture, 11% is incinerated for energy recovery, 40% is landfilled and 12% is used for other purposes, mainly in forestry and drainage (Grobelak et al., 2016). To be suitable for application, municipal sewage sludge follows a sedimentation process, then it is digested by microorganisms. Finally, nitrogen and phosphorus are chemically removed from the waste (Goss et al., 2013; Kumar, 2016; Ansari et al., 2019). Table 6 presents the examples of sewage sludge which can be used as soil enhancers.

Tab.6. Characteristic of sewage sludge as soil enhancers.

No.	**Parameters**	**C**	**N**	**P**	**OM**	**pH**	**References**
	Units	%				-	
1	Sewage sludges	+*	<2.0	<1.5	50	+	Kosobucki et al., 2000
2	Sewage sludges	+	0.55	15.88	14.71	5.52	Chu et al., 2017
3	Sewage sludges	+	12.13	22.30	81.21	6.65	
4	Sewage sludges from Thailand	+	3.43	+	19.82	6.82	Sing et al., 2008
5	Sewage sludges from Spain	+	2.5	1.06	43.4	8.6	
6	Sewage sludges from India	+	2.6	1.34	23.2	7.1	
7	Domestic sewage sludges	+	16	7.0	19.4	8.20	Jamil et al., 2006

+* is present, but the exact content has not been specified.

The chemical composition of sewage sludge and biodegradable fraction of municipal solid waste can significantly differ. This is affected by the wastewater that is mixed and enters the wastewater treatment plant. The waste which are includes kitchen waste, garden waste, household waste, paper, and inorganic items such as plastic, rubber, metal, glass, and ceramics (Nanda et al., 2020).

Algae

Algae are another substrate that can be used to produce soil enhancers. Algae are used in the food, cosmetic and pharmaceutical industries, as well as in agriculture. Green algae, brown algae and red algae are used to produce soil enhancers. Algae have a higher nitrogen content and a lower C/N ratio than plant biomass (Han et al., 2014). Table 7 presents the fertilizing potential of algae as soil enhancers.

Tab.7. Algae as substrate for production of soil enhancers.

No.	**Parameters**	**C**	**N**	**P**	**OM**	**C/N**	**References**
	Units	%					
1	Green algae	19.5-26.3	3.6	+	53.3	5.4-7.3	Han et al., 2014
2	*Ulva* sp.	5.78-24.3	0.68-2.77	+	13.7-41.97	8.5-8.78	
3	Blue-green algae	36.3-44.9	7.4	+	62.1	4.9-6.06	
4	*Undaria pinnatifida*	31.32-36.9	2.67-4.14	+	+	8.92-11.7	
5	*Posidonia oceanica*	36-46.2	0.6-1	+	+	36-81	
6	*Fucus* sp.	+	1.84	9.2	+	11.2	Michalak et al., 2016

+* is present, but the exact content has not been specified.

Algae are being studied for their use in bioremediation and biomonitoring, for biofuel production, a base for biopolymer production and in the food industry (Araújo et al., 2021). In 2016, over 32 Mt of algae biomass was produced in the world, which 0.57% in Europe (mainly Great Britain, Iceland, France, and Norway) (Araújo et al., 2021).

Biopolimers

In recent years, there has been a growing interest in the use of biodegradable and compostable plant-based products that can be used in growing plants. The term bio-

biodegradable and plant-based applies to a polymer that is produced from the plant biomass. The term biodegradable refers to the ability of the material to decompose into natural components (water, carbon dioxide and microorganisms) (Moshood et al., 2022).

Currently, bioplastics (including biodegradable/compostable plant-based products) account for 1% of the 367 million tons of plastics produced annually. In the case of bioplastics, about 36% of them are not biodegradable, which is about 870,000 tons. Global bioplastics production is expected to increase from 2.42 million tons to 7.59 million tons between 2021 and 2026 (European Bioplastic, 2021). Bioplastics are mainly used in packaging, electronics, automotive, agriculture, horticulture, construction, and other economic sectors. Asia is the leading producer of bioplastics (49.9%), followed by Europe (24.1%), North America (16.5), South America (9.1%) and Australia (0.4%) (European Bioplastic and nova-Institute, 2021). Bioplastics are produced based on polybutylene adipate terephthalate (PBAT), polybutylene succinate (PBS), and polyamide (PA) and polylactic acid (PLA) (European Bioplastic, 2021).

All bioplastic-based products, according to European standard EN-13432, are required to be more than 90% degradable within 6 months to be referred to as biodegradable. The international standard ASTM D6954, in turn, indicates that a biodegradable product is expected to degrade completely within two years. However, these are guidelines describing product degradation under laboratory conditions without comparing degradation rates in other environments (Di Bartolo et al., 2021; Rosenboom et al., 2022). Under aerobic conditions, biodegradable plastics decompose into carbon dioxide, minerals, and water (in 20-45 days). However, under anaerobic conditions, biodegradable plastics decompose into carbon dioxide and methane. The degradation process is also supported by the biomass of microorganisms. The decomposition time depends on the availability of oxygen, humidity, and the quantity of microorganisms (Moshood et al., 2022).

Biodegradable/compostable plant-based products, as opposed to conventional plastics, can be also considered to use as soil enhancers. Plant-based products can also be compostable, allowing them to be composted with various organic wastes. However, there is no specific legislation that describes the requirements that biodegradable/compostable plant-based products must achieve to be used as soil enhancers. According to EN 13432, a product can be referred to as compostable if at least 90% of the fraction is fragmented to <2 mm, within 12 weeks and fully mineralized within 6 months. The remaining 10%, can be converted to biomass or fragmented as microplastics. The finished compost should not contain heavy metals and be toxic to the environment (Steinera et al., 2022).

One of example is the use of cornstarch-based biodegradable films in agriculture for mulching plants. Biodegradable film protects plants from weed growth, while after the season, it degrades naturally on the soil or can be collected and composted with other waste (Dróżdż et al., 2022; Moshood et al., 2022). Biodegradable films can contain an additive fill of various nutrients, antimicrobial substances and additives that affect the stretchability and decomposition time of plant-based plastics. These treatments qualify biodegradable/compostable plant-based plastics as soil enhancers. In the literature, there are reports of the addition of cellulose-based biodegradable materials, cellulose nanocrystals, agar, silica, lignin, wood flour, seed meal and plant fibers to films (Mittal et al., 2015; MC Branciforti, et al., 2019; Balaji et al., 2020). Biodegradable films can also contain antimicrobial carriers based on sorbic acid, benzoic acid, triclosan, citrus seed extract and bacteriocins (Soldo et al., 2020; Richert et al., 2021). The effect of microorganisms on the decomposition of biodegradable/compostable plant-based products, can also be modified. The use of substances that reduce the number of microorganisms that cause the decomposition of biodegradable/compostable products helps to extend the applicability of these products. This is especially important for biodegradable mulch films. Richert et al, (2021) applied birch tar filler to produce biodegradable films (PLA) with antimicrobial properties. Concentration of 10% birch tar in PLA-based biodegradable films, reduced the hydrolytic activity of PLA film degraders (microorganisms) significantly. Slower biodegradation of the film was also dependent in addition to the filling concentrations but also on temperature and humidity.

The residues of biodegradable/compostable plant-based products can also be used as substrates for other biological and thermal processes. Pudełko et al., (2022), produced biocomposites based on PLA, BIOPLAST GS2189 and with the addition of filler in the form of biochar and sewage sludge. The result was the production of clips and plant supports, i.e., tomatoes. The addition of 20% biochar had a positive effect on the mechanical and thermal properties of the clips. It was suggested that after the plant growth period, the plant residues and clips could be composted to reduce waste and produce full-value compost. The Neptune Plastic team reached similar conclusions regarding the compostability of biodegradable products. They developed a material that can be composted in a home garden, and the obtained compost can be used as fertilizer. Another example of the use of biodegradable products as fertilizer is their exposure to aqueous ammonia and high temperature (around 90°C), from which urea is formed. Urea obtained by chemical recycling can be used as soil enhancers for fertilization purposes (Rosane, 2021).

Biodegradable/compostable plant-based products, can also be used as a substrate in anaerobic digestion to obtain biogas and solid state digestate. Solid state digestate can be used in further processes as a substrate for compost production (Vardar et al., 2022).

The topic of using biodegradable and compostable products as soil enhancers is progressively being developed. However, this topic still requires detailed research on the environmental impact of biodegradable products.

All the above-mentioned plant, animal and mineral-based substrates can be used through biological, chemical, and physical processes to produce soil enhancers. According to the literature, soil enhancers can be produced by composting (Walker et al., 2008; Awasthi et al., 2020; Wan et al., 2020, Awasthi et al., 2021), anaerobic digestion (Bujoczek et al., 2000; Singh et al., 2011; Rodriguez-Verde et al., 2018; Pan et al., 2019), pyrolysis (Das et al., 2008; Agblevor et al., 2010; Hass et al., 2012; Cimo et al., 2015), drying (Buckner, 1926; Ghaly et al., 2012; Ghaly et al., 2013; Bao et al., 2020), energy recovery from the combustion and using it for heating henhouses (Clarke, 2019), pelletizing/granulation (Jackson et al., 2006; Mazeika et al., 2016; Zdanowicz and Chojnacki, 2017; Feng et al., 2019), and their application in untreated form directly to the soil (Loyon, 2018).

The obtained products, i.e., compost, biochar, pellets/granules, ash with fertilizing potential, can be used in agriculture as soil enhancers to improve soil properties and plant growth and yield (Ansari et al., 2019). Soil enhancers, has a positive impact on the protection of the environment and reduces the loss of valuable nutrients from animal, plant, and mineral-based substrates. The use of substrates based on plant residues supports the concept of sustainable and circular agriculture (Mazeika et al., 2016; PARP, 2022).

1.2. Effects of organic soil enhancers on soil properties

The soil, it is one of the main components of the environment. Constantly is exposed to various changes, especially in the properties and the chemical composition and different weather and climatic conditions. These situations generate biotic stress (from animate nature, e.g., pathogens) and abiotic stress (from inanimate nature, e.g., soils drought) in plants and soil microorganisms (Shahbaz et al., 2017; Ansari et al., 2019).

Chemical properties

The application of chemical fertilizers and pesticides has negative effects on soil. It causes difficulty in carbon sequestration, increases C/N ratio (>30: 1) and pH (> 7.0). Excessively high values C, N and pH prevent plants from absorbing nitrogen and carbon for proper growing plants and cause depletion of soil microbial colonies. Difficulty in carbon storage and absorption by plants is also related to the mineral content of the soil, i.e., sand, clay, and carbonates (Scotti et al. 2015; Wang et al., 2017; Ansari et al., 2019).

To reduce the use of chemical fertilizers, the alternative solution is to produce and use organic soil enhancers. Soil enhancers influence on soil structure and contribute to increase oxygen availability in the soil through pore-formation (Yang et al., 2022). Soil with soil enhancers accumulates larger amounts of water. This improved the effective use of water by microorganisms and plants, increased migration of nutrients with water (Wang et al., 2017; Jiang et al., 2018), enhanced gaseous diffusion (Guo et al., 2019; Wang et al., 2019). Changing soil properties with soil enhancers improves crop yields and contributes to damaging plant resistance to drying and reducing soil erosion (Li et al., 2014; Yang et al., 2022).

The soil and the microorganisms and plants that exist in the soil, require basic elements to function properly especially nitrogen, phosphorus, and carbon. Depending on the soil enhancers applied, nitrogen and phosphorus concentrations can vary significantly. For example, Edmeades (2003) and Cela et al. (2010) estimated that if the nitrogen content is sufficient for a specific crop and soil, the phosphorus, potassium, and magnesium content can be higher than the plant requirement for these nutrients. Plants can accumulate 1 to 4% nitrogen and potassium in stalk. In plant stalk, phosphorus content is between 0.2 and 0.4% in the dry weight. Nitrogen and phosphorus are available in soil enhancers in organic and inorganic forms and the potassium is available in inorganic cation (Goss et al., 2013; Ansari et al., 2019).

However, the use of soil enhancers is not always associated with soil benefits itself when they are applied. Soil enhancers can also generate undesirable effects in the chemical properties of the soil. Although soil enhancers are introduced to soil to improve the properties and plant growth. Composts produced from organic fraction of municipal waste could have negative effects on soil and plant, e.g., compost increases the electrical conductivity of the soil and subsequently increases soil salinity, which can be toxic to the plants. This problem was noted by Bonanomi et al. (2011a, b) who applied municipal waste compost to plant crops in foil tunnels. The excessive salinity in tunnel crops was due to the absence of natural leaching and migration of organic matter deeper into the soil profile. A similar conclusion was reached by

Mohsenzadeh et al., (2019) who compared the effects of municipal solid waste compost and vermicompost on plant growth. They found that the use of municipal solid waste compost, due to its high salt and organic matter content was toxic to the plant. However, El Hasini et al., (2020) used the compost based on plant biomass and sheep manure to prevent soil salinity. The obtained compost, with C/N ratio of 35:1, influenced in reducing soil salinity.

The release of nutrients depends on the type of soil enhancers, the soil type, the weather and climatic conditions, residues from other fertilizers, and the agricultural practices practiced in the field. Due to the numerous variables involved, it is often impossible to apply precise doses of soil enhancers and synchronize them with the current nutrient requirements of plants (Goss et al., 2013; Ansari et al., 2019).

Physical properties

The improvement of soil properties after the application of soil enhancers includes not only the increase in organic matter, but also changes of the physical properties of the soil. This includes improvement in soil porosity, increased water absorption, improved carbon sequestration, stabilization of soil aggregates and reduces the bulk density of the soil (Bhowmik et al. 2016, 2017; Ansari et al., 2019). Soil aggregates enable larger amounts of oxygen to be transported to the deeper layers of the soil through the pores. Improving aerobic conditions has a beneficial effect on soil microorganisms (Scotti et al. 2015).

Biological properties

It has been observed that if the soil is deficient in organic matter and there are no sources of additional organic matter (such as soil enhancers), microbial biomass is reduced (Bonanomi et al. 2011a; Ansari et al., 2019). For example, the addition of compost to soil deficient in organic matter increases the activity of microorganisms, and thus the enzymatic activity of β-glucosidase, dehydrogenase and phosphomonoesterase. This leads to the enhancement of microbial colonies that affect soil fertility. The addition of manure-based compost or green waste to soil increases the biodiversity of microorganisms that are difficult to count and determine their types (Scotti et al. 2015; Whitman et al. 2016; Zheng et al. 2017; Dimitrow et al. 2017).

1.3. Legal and environmental aspects

Legal aspects related to soil enhancers

Organic soil enhancers must fulfill the requirements set out by the legislation in force. Soil enhancers must comply with safety and quality requirements depending on their intended use. In particular, the content of heavy metals, pathogenic microorganisms, nitrogen, and phosphorus, as well as micro- and macro elements are verified. All this information can be found in the Fertilizing Product Directive (Regulation (EU) 1009/2019), of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

Soil enhancers obtained through biological, chemical, and physical processes are required to comply with several requirements, before being approved for the use in agriculture. Table 8 presents some of the requirements for soil enhancers which are imposed by the legislation in force.

Tab.8. Requirements for soil enhancers.

Elements	Permissible limits for soil enhancers
Heavy metals, dry weight	
Cd	2 mg/kg
Cr VI	2 mg/kg
Hg	1 mg/kg
Ni	50 g/kg
Pb	120 mg/kg
As	40 mg/kg
Cu	300 mg/kg
Zn	800 mg/kg
Microbiological tests	
Salmonella spp.	Bacteria do not present in 25 g or 25 ml of test solution.
Escherichia coli or *Enterococcaceae*	Acceptable 1000 CFU * in 1 g or 1 ml of test solution.
Organic matter content, dry weight	
Soil enhancers should contain at least 20 %.	
Organic carbon content, dry weight	
Soil enhancers should contain at least 7.5%.	

*Colony forming unit (CFU).

On July 16, 2022, the regulation revising the 2019 version of Fertilizing Product Directive-Regulation (EU) 1009/2019, was come into practice (Safe and Effective Fertilizers on the EU Market, 2022). The updated regulation includes information on toxicity limits for substances, in organic fertilizers, soil enhancers, organic-mineral fertilizers, bio stimulants and growing media. Fields of application for safe use of fertilizing products, their quality, minimum organic content, and labeling will also be included.

The update Fertilizing Product Directive (Regulation (EU) 1009/2019), have enabled the opening of the single market for fertilizing products where new types of substrates of a fertilizer nature are required to be registered under EU REACH regulations. These categories of substrates include substances and mixtures of raw materials, composting additives, mineralization additives and by-products of the food industry. This regulation provides novel opportunities for new and innovative organic fertilizing products. The Component Material Categories (CMCs) required to be registered under REACH include CMCs 1 through 14. Table 9 presents, each category.

Tab.9. Component Material Categories (CMCs) (Regulation (EU) 1009/2019 from 16 July 2022).

Number of CMC	Designation of CMCs
CMC 1	Virgin material substances and mixtures.
CMC 2	Plants, plant parts or plant extracts.
CMC 3	Compost.
CMC 4	Fresh crop digestate.
CMC 5	Digestate other than fresh crop digestate.
CMC 6	Food industry by-products.
CMC 7	Micro-organisms.
CMC 8	Nutrient polymers.
CMC 9	Polymers other than nutrient polymers.
CMC 10	Derived products within the meaning of Regulation (EC) No 1069/2009.
CMC 11	By-products within the meaning of Directive 2008/98/EC.
CMC 12	Precipitated phosphate salts and derivates.
CMC 13	Thermal oxidation materials and derivates.
CMC 14	Pyrolysis and gasification materials.

The categorization of Product Function Categories (PFCs) has provided an ability to harmonize safety and quality rules for fertilizing products that will be permitted for sale in markets all over the European Union. Producers of organic fertilizers are subject to the Fertilizing Product Directive, which provides for the launch of new products that until now were not included in the regulations. For farmers, the new regulation expands the choice of fertilizing products, price competitiveness and attention to product quality versus environmental impact.

Limits on heavy metals and pathogens are intended to provide increased soil protection, reducing health and environmental risks compared to chemical fertilizers. The new regulation also aims to promote the use of organic waste to produce soil enhancers as fertilizers. These operations are aimed at supporting circular economy and encouraging farmers to use natural fertilizers. Sustainable agriculture is also the goal of many organic fertilizer producers, who until now, have not been specifically covered by harmonized national and international regulations (NUTRIMAN 2022; Regulation (EU) 1009/2019 from 16 July 2022).

Environmental aspects of the application of soil enhancers

Soil enhancers use organic waste from agriculture, food processing, and plant biomass. The use of organic waste in thermal, biological, and chemical processes gives the resulting soil enhancers new fertilizer properties. Therefore, retention the loss of micro-and macronutrients and reduce excessive storage of waste (PARP, 2022). Production of soil enhancers is an effective method to obtain products with fertilizing potential. It supports the approach of sustainable agriculture which puts a strong emphasis on the use of safe, efficient, and cost-effective soil improvement products (CDR, 2017).

Although applying soil enhancers containing macro and micro-nutrients is beneficial to soil and soil microorganisms, but some soil enhancers can pose potential risks. Soil enhancers based on organic fraction of solid municipal waste can contain some heavy metals, pathogens, chemical runoff from industry, roads, and parking areas. In addition, manure-based soil enhancers can be affected by the presence of antibiotics, pesticides, growth hormones, heavy metals, pathogenic microorganisms such as *Salmonella* or *Escherichia coli*, fungi, *Cryptosporidium* and *Giardia* spp. parasites. Green manures can also contain chemical fertilizer residues, pesticides, road dust and exhaust in the form of polycyclic aromatic hydrocarbons, microplastics such as polyethylene, polyvinyl chloride, polypropylene, polystyrene, polycarbonate, polyamide, and polyethylene terephthalate (Zhao et al, 2010; Patyra et al, 2018; Muhammad et al, 2020; Deng et al, 2020; Adekanmi, 2021; Wu et al, 2021).

For example, biochar as a soil enhancer increases the sorption of plant nutrients and can immobilize heavy metals and organic pollutants, i.e., dioxins and polycyclic aromatic hydrocarbons. This association is dangerous when biochar is exposed to intensive leaching from soil. Contaminants accumulated by biochar can be released into surface waters, causing negative environmental impacts (Ślęzak et al., 2018; Poluszyńska et al., 2019).

Techniques of in-soil application of soil enhancers can also cause some risks to the environment. The application of soil enhancers is used in form of solid and liquid. The method of application depends on the type of soil enhancer. If a liquid form is used and injected into the upper layers of the soil, extensive nitrogen loss in the form of ammonia can be observed. Also, when the liquid form is used, bioaerosols and dusts can be formed in the soil, which can affect the nearby areas, air, and water. To avoid the most unfavorable time to use soil enhancers, i.e., summer (drought and dust, plant growth) and winter (unfavorable temperature conditions, lower nitrogen recovery by plants, susceptibility to leaching), fertilizers should be applied in spring and fall (Fleming and Fraser, 2000; Goss et al., 2013; Ansari et al., 2019).

2. Poultry manure as a resource to produce organic soil enhancers

According to the Food and Agriculture Organization of the United Nations (FAO), the world's poultry production in 2019 exceeded 27.9 billion units. Compared to 2000 (14.38 billion units), it has doubled. Almost 93% is poultry, the rest is ducks, geese, and turkeys. The dominant countries are China (Asia), the United States (North America), Brazil (South America and Poland (Europe) (FAO, 2019). Such intensive poultry production generates significant amounts of manure which is consider a challenge when it comes to handling, managing, and processing of this type of waste. Poland has the highest annual production of poultry manure in Europe (more than 4 mln Mg/year). Therefore, there is a potential for converting the poultry manure into soil enhancers in Poland (Tanczuk et al., 2019). Raw poultry manure can be a soil enhancer, but it can also be a substrate for e.g., dried/pelletized poultry manure, poultry manure derived biochar and compost. The use of poultry manure affects the possibility of reducing the application of chemical fertilizers which release nutrients fast into soil. In case of poultry manure is a fertilizer which slowly release the required organic matter to soil. Therefore, they reduce the requirement for extensive soil fertilization (Shaji et al., 2021).

Also in the literature, the authors have frequently used poultry manure as a soil enhancers and growing media. The scientific publications have concentrated on the aspect of the effect of poultry manure in improving soil properties and compared plant growth with poultry manure application at different doses (Augustyńska-Prejsnar et al., 2018; Mbah et al., 2018; Adekiya et al., 2019; Loh et al., 2019; Mpanga et al., 2021). Another way to manage poultry manure is to mix it with biochar to increase fertilizer properties and reduce gaseous emissions during the composting process (Barnossi et al., 2020; El-Mageed et al., 2021). Kyakuwaire et al., (2019) and Adekiya et al., (2019) described the physicochemical parameters of obtained compost and biochar and their beneficial effect on nutrient retention. However, Poblete-Grant, et al., (2019), Adnad et al., (2019) and Kacprzak et al., (2022) focused on characterizing nutrient availability, especially in cycles C, N, and P during the processing of poultry manure. Aylal et al., (2018), Awasthi et al., (2021), Zhou et al., (2021), Sobik-Szołtysek et al., (2021) observed the impact of biochar application and the potential for heavy metal accumulation. Jurgutis et al., (2020), Chung et al., (2021) focused on greenhouse gas emissions when using poultry manure as a fertilizer. Biochar from poultry manure also demonstrates immobilization and gas absorption properties.

2.1. Generation of poultry manure

In 2020, the annual poultry production was estimated at 182,473,350 heads in Poland. According to the EUROSTAT data from 2021, Poland achieved the highest index of poultry production (EUROSTAT, 2021).

Polish farms are predominated by cage breeding system at almost 87%, followed by the litter breeding system at 10%, free-range at 3%, and organic system at less than 1% (National Chamber of Poultry and Feed Manufacturers, 2018; Dróżdż et al., 2020). The differences between the four types of poultry breeding are briefly explained in the following paragraphs.

Cage system

Cage breeding is characterized by higher poultry house density and lower production costs per egg. This type of farming results in a lower price of the product. Also, the final product, eggs, presents more stability in terms of quality and microbiological safety (Drabik et al., 2018; Bioeggs, 2021). Legal regulations regarding the appearance and size of cages specify that the producer must provide about 750 cm^2 of cage area for one laying hen (CDR, 2013). There are almost 40 million laying hens in cage breeding in Poland. The average size of a poultry house in Poland is 85,000 poultry. This compares to about 45,000 poultry in Europe (Parkiet, 2021).

Litter system

The litter breeding system is characterized by the fact that the poultry house is lined with litter: grain straw, wood chips or peat (Myszograj et al., 2012). The litter insulates the poultry from the ground and absorbs moisture. The floor in litter poultry housing should be at least $^{1}/_{3}$ covered with litter. Deep litter (almost 15 cm) is most used and is the healthiest for the birds. Birds can walk around the poultry house freely, choose nests and sit on perches. However, they cannot go outside. Eggs from this type of breeding can be microbiologically less safe than eggs from hens kept in cage breeding, because the eggs from litter system come in contact with the litter which contains poultry manure. Birds in this type of breeding can also receive feed that contains genetically modified (GMO) ingredients (Bioeggs, 2021).

Free-range system

Free range breeding is characterized by the fact that the birds live in a poultry house and has access to a perch, but in contrast to the cage or litter system has unlimited access to the outdoors. This allows the birds to scratch their claws, perform sand baths, and get food on independently. In a free-range system, there are 9 birds per 1 m^2 and each bird should have 4 m^2 of outdoor run (Bioeggs, 2021).

Organic system

The organic system is characterized by higher requirements for breeding, poultry houses, stocking density, animal feeding equipment, ventilation systems and microclimate. According to the legislation, in organic system there should be 6 laying birds per 1 m^2. The poultry house area should be a maximum of 1600 m^2. An important aspect in organic system are also the microclimatic conditions in the poultry house where the temperature should be at 21-22°C and the humidity at 60-70%. Birds needs about 14-16 hours of light to lay enough eggs. Organic system has unlimited access to the outdoors (Bioeggs, 2021; Drabik et al., 2018).

The amount of poultry manure produced depends on the type of poultry being raised. One adult laying hen per day can eat between 90 and 160 g of feed depending on the season (Bas-Pol, 2018). A broiler eats 100 to 170 g up to twice a day during weight gain (Drabik et al., 2018; SuperMG, 2021).

It is estimated that one adult hen produces between 150 and 160 g of manure per day, while a young hen in the range of 65 to 100 g. Dancechuk et al. (2019) in their work assumed that laying hens and boilers daily produce 110 g and 65 g, respectively. The calculations by Tańczuk et al. (2019) indicate that the annual production of poultry manure in Poland exceeds 4 mln Mg. Laying hens produce 2.1 mln Mg of manure annually, while broilers produce 2.3 mln Mg (Tańczuk et al., 2019). Figure 1 shows the numerical distribution of poultry manure production by voivodeship and type of poultry production (Tańczuk et al., 2019; Dróżdż et al., 2020).

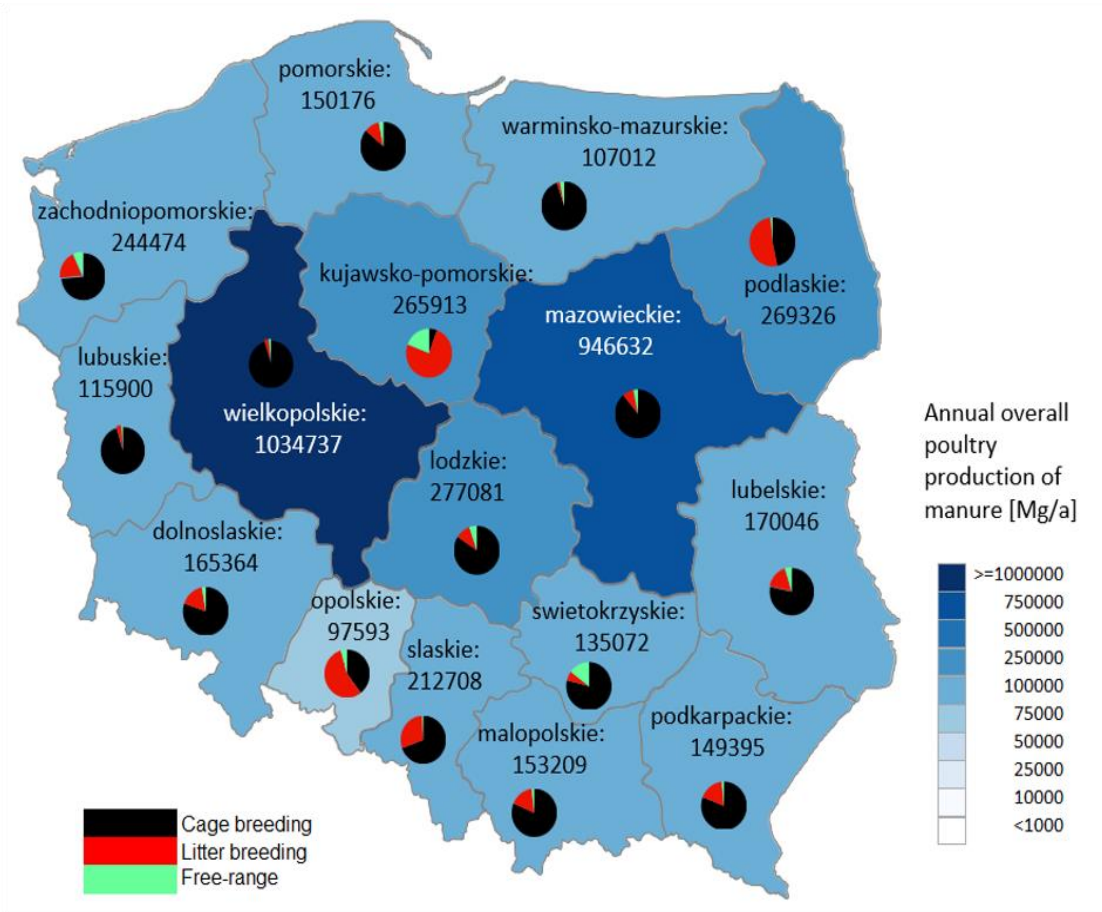

Fig.1. Production of poultry manure in Poland with distinction on voivodeships and types of poultry breeding (Dróżdż et al., 2020).

The annual production of poultry manure from cage breeding is over 1.8 mln Mg. The leading voivodships are: Wielkopolskie (0.6 mln Mg/year), and Mazowieckie (0.3 mln Mg/year) and Małopolskie (0.08 mln Mg/year). Whereas, from litter breeding it is about 0.2 mln Mg with leading voivodships of: Mazowieckie (0.04 mln Mg/year), Podlaskie, and Śląskie

(0.03 mln Mg/year). Poultry manure generated in free-range breeding is estimated at 0.06 mln Mg/year, and the leading voivodships are as follows: Mazowieckie (0.5 mln Mg/year), Wielkopolskie (0.3 mln Mg/year), and Podlaskie (0.2 mln Mg/year) (Tańczuk et al., 2019; Dróżdż et al., 2020).

2.2. Characteristics of poultry manure

According to the Regulation of the European Parliament and of the Council (EC) No. 1069/2009, poultry manure is included in category 2, i.e., animal by-products. It can be used to produce soil enhancers and organic fertilizers.

Poultry manure is defined as a mixture of poultry excrement, feathers, soil, feed residues, water, urine and depending on the type of breeding, also litter (Ashworth et al., 2020). Depending on the type of poultry raised, i.e., ducks, hens, geese or turkeys, the amount of manure produced differs depending not only on the produced quantities but also on the chemical composition. Comparatively, 1000 turkeys per day produce 160 kg of manure, 1000 geese 200 kg/day, 1000 ducks 190 kg/day, and 1000 laying and broiler hens from 65-155 kg/day (Dróżdż et al., 2020; Ashworth et al., 2020). The amount and composition of poultry manure produced depends significantly on the age of the poultry, the does and composition of the feed and water they consume. The average annual production of poultry manure per 1 m^2 of building is 200 kg (Myszograj et al., 2012).

Poultry manure is a valuable source of K, P, N, Ca, C, Zn, Cu, Se. It contains 68–73% water, 1.24–2.31% nitrogen, 0.48–0.68% phosphorus and 0.36–0.59% potassium (Augustyńska-Prejsnar et al., 2018). Nitrogen in poultry manure occurs mainly in the form of uric acid 40-70%, ammonium from 4 to 20%, urea from 4 to 12%, and nitrogen of feed protein from 10 to 40% of the content (Augustyńska-Prejsnar et al., 2018; Dróżdż et al., 2020). The ratio of C/N for poultry manure from laying hens ranges from 4:1 to 18:1. For manure from broiler litter are 6:1 to 24:1 C/N (Wortmann et al., 2012).

Depending on the type of a system, table 10 presents the content of Fe, Cu, Zn, Mn, Ca, and Mg for poultry manure from different types of breeding.

Tab.10. The content of Fe, Cu, Zn, Mn, Ca, and Mg for different types of breeding in poultry (Amanullah et al., 2007; Augustyńska-Prejsnar et al., 2018).

Elements	**Ca**	**Cu**	**Mn**	**Mg**	**Fe**	**Zn**
Units	%	ppm				
Deep litter	0.9-1.10	24-42	210-380	0.45-0.68	970-1370	90-308

Broiler house	0.86-1.11	27-47	190-350	0.42-0.65	970-1370	160-315
Cage manure	0.8-1.02	80-172	370-590	0.4-0.56	970-1450	290-460

Depending on the type of poultry breeding, the results of Fe, Cu, Zn, Mn, Mg, Ca content can be different. The highest results were obtained in poultry manure from cage breeding. It is clean manure with no litter added. Therefore, the values from the cage breeding of poultry manure are more cumulative than in the rest of the poultry manure breeding (Amanullah et al., 2007; Augustyńska-Prejsnar et al., 2018).

2.3. Environmental risks related to the use of poultry manure

Poultry manure can contain substances and microorganisms that have the potential to generate adverse reactions in soil, air, water, and human and animal health. The potential sources of hazards during the handling, processing of poultry manure and using poultry manure-based products are related to the presence of antibiotics, heavy metals, pesticides, pathogenic microorganisms as well as generation of gaseous emissions and contamination with microplastics.

Antibiotics

The main problem associated with the presence of antibiotics in the environment is the effect of antibiotic resistance. Excessive doses of antibiotics cause the bacteria that were supposed to be controlled by them to become resistant to their effects. As a result of the accumulation of antibiotics in the human body, approximately 7 million people die each year worldwide (Patyra et al., 2018; Muhammad et al., 2020).

It should be noted that 100% of medications are never metabolized in the body (animal, human). The medications are usually metabolized in around 50-60%. For example, antibiotics containing amoxicillin or tetracyclines (about 10-20% degradation) are less able to be degraded while antibiotics containing sulfamethoxazole are mostly degraded (almost 85%). The residues are excreted in feces and urine. In agriculture, the same medications are often used for animals and humans. Annually, several thousand tons of antibiotics enter the environment along with animal feces (Christian et al., 2003; Zhao et al., 2010).

Tetracyclines (almost 80-90%), chlortetracycline (70-80%), chloroquine and erythromycin (70%), lincomycin (60%), tylosin (40-50%), and metronidazoles (30-40%) get into the environment mainly from the animal faeces and urine. The migration of antibiotics into the soil depends mostly on the soil type, climatic conditions, the organic matter content, and the number of soil microorganisms, in addition to the decomposition time of the chemical compounds. Antibiotics, such as tetracyclines, can be absorbed strongly by clay and sedimentary soils (Muhammad et al., 2020). Organic matter encourages the accumulation of antibiotics, including fluoroquinolones and sulfonamides, and remains unchanged for a relatively long time. Most antibiotics are found in the soil at a depth of 10 to 30 cm. The concentration of antibiotics in the soil can reach 198 g/kg of tetracyclines and 7.3 g/kg of chlortetracycline which are most used in poultry breeding (Muhammad et al., 2020). Gentamicin, neomycin, lincomycin, penicillin, erythromycin, tylosin, sarafloxacin, enrofloxacin, bacitracin, monensin, salinomycin, semduramycin, bambermycin, chlortetracycline, oxytetracycline, tetracycline, can be found in poultry feces. These groups have anti-infective functions, stimulate growth, and increase feed efficiency (Muhammad et al., 2020; Hamscher et al., 2005).

High concentration of medicines in the natural environment can have a negative impact on the formation of antibiotic-resistant bacteria, reduction of primary microorganisms inhabiting the soil/water, improper development of animals, e.g., fish, i.e., rainbow trout, in their body the developed reproductive organs were smaller than standard. The use of growth hormones caused cardiac hypertrophy in poultry. Assimilation of antibiotics from vegetables and fruits causes inflammation in the liver after exposure to diclofenac. Overexposure to antibiotics slowed the growth of embryonic cells and causes difficulties in treating bacterial infections due to antibiotic resistance in humans and animals, etc., (Muhammad et al., 2020).

Heavy metals

Heavy metals (zinc, copper, chromium) have been detected in feces, potentially causing long-term soil contamination and migration to surface water. Other contaminants that can be found in poultry manure include cadmium, nickel, and lead. Excessive quantities can come from improperly prepared, contaminated feed, animal contact with industrial wastewater, medicines, etc. (Deng et al., 2020).

However, to avoid further propagation of heavy metals with soil enhancers and growing media, they must follow the requirements of the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization from 2007. The permissible values for heavy metals should not exceed: chromium < 100 $mg*kg^{-1}$ dry matter, cadmium < 5 $mg*kg^{-1}$ dry matter, nickel < 60 $mg*kg^{-1}$ dry matter, lead < 140 $mg*kg^{-1}$ dry matter.

Pesticides

Pesticides are mainly used in plant cultivation but also in animal husbandry. Pesticides can be divided into fungicides, intended to eliminate fungi, against insects (insecticides) and weeds (herbicides) (Now Environment, 2015). The total number of active substances used annually in plant and animal protection products is 350,000 tons in the EU (European Court of Auditors, 2020). Plant and animal protection products are substances that can also constitute a threat to the environment if inappropriately managed. One of the problems in poultry breeding are parasites, including *Cryptosporidium* and *Giardia* spp. that contribute to gastrointestinal disorders in humans and animals. These protozoa cause acute diarrhea that often leads to exhaustion and possibly death. *Giardiasis* and *cryptosporidiosis* are particularly dangerous for young animals, animals chronically treated with pharmaceutical medicines, and older animals (Veterinary Medicine, 2018). Another parasite affecting poultry is *Dermanyssus gallinae,* or the so-called "red mite." It is difficult to control the mites which cause the transmission of pathogenic microorganisms such as *Salmonella*. Most parasites are treated with detergents, insecticides and high-temperature methods that should not be detected and do not affect meat, eggs, or poultry manure.

Microbiological hazards

Poultry manure can contain not only pathogens but also algae that are posing a significant threat to the environment, and thus to living organisms (Michalak et al., 2016; Bougarne et al., 2019). As a result, other plants growing in crop fields can be contaminated. This is dangerous because microorganisms, because of antibiotic use, develop resistance and are more difficult to eliminate.

In poultry litter, on eggshells, and in poultry manure, scientists have identified the presence of *Escherichia coli, Globicatella, Listeria, Mycobacterium, Salmonella, Actinobacillus, Bordetella, Campylobacter, Clostridium, Corynebacterium, Staphylococcus,* and *Streptococcus*. *Salmonella, E. coli, Campylobacter*, and *Actinobacillus* are particularly common and can be present in above 50% of poultry manure (Magdy, 2017; Kyakuwaire et al., 2019; Adekanmi, 2021). *Escherichia coli* causes swelling, diarrhea, and blood in the feces in the human and animal body. *Salmonella* and *Clostridium* are responsible for nausea, fever, headaches, dehydration, and general body debility. *Campylobacter* and *Staphylococcus* paralyze muscles, and *Listeria monoctgogenes* can cause labor early in pregnancy (Kyakuwaire et al., 2019).

Providing the water with significant amounts of nitrogen and phosphorus from poultry manure can cause eutrophication. Highly intrusive algal bloom can reduce the availability of oxygen aquatic microorganisms and fish. Causing the growth of toxic algae such as *Pfiesteria piscicida*, which produces toxins that damage the skin of fish and in larger quantities lead to fish death. It can also be harmful to humans (SmogLab, 2019; Bougarne et al., 2019).

Gas emissions

Gas emissions from poultry farms are especially harmful to the environment as well to living organisms. In addition, the construction of farms depends on many aspects, such as the size of the poultry house and the distance from residential buildings.

To comply with all these requirements, farmers need to obtain several permits from their legal entities to build such a facility. Often, the construction of a farm is opposed by residents whose buildings will be adjacent to the farm. The residents are concerned about odors, gas emissions, and leachate from the farm that can end up in the soil and surface water (Myszograj and Puchalska, 2012; Dróżdż et al., 2020).

The most common gases released from farms include ammonia, methane, nitrous oxide, sulfur dioxide, nitrogen dioxide, carbon monoxide, $PM_{2.5}$, and PM_{10} dust. Poultry breeding can also release dimethylamines, aldehydes, ketones, organic acids, as well as carbon dioxide and other odors (Swelum et al., 2021; Dróżdż et al., 2020).

The quantities of produced gases and dust depend on the type of breeding, bedding, poultry house stocking, geographic location, season, and nutrition (Myszograj and Puchalska, 2012).

Table 11 presents a literature summary on the content of gases and dust generated during poultry farming and poultry manure.

Tab.11. Quantities of emitted gases and dust from poultry breeding.

Compound emitted into the atmosphere	Quantity of compounds	Type of breeding and number of poultry	References
Ammonia – NH_3	12-40 t/year	From 110 000 broilers	EIP, 2018
Methane – CH_4	80 kg/year	1000 hens	Dróżdż et al., 2020
Nitrous oxide – N_2O	0.25 kg/year	From one-layer hens	Broucek, 2018
	1.39 kg/year	From one broiler	
Sulfur dioxide – SO_2	15-60 g/kg	Per kg liveweight broiler	Ogino et al., 2021
Dinitrogen oxide – N_2O	0.58-1.15 g/kg	From one broiler	Agrotech, 2011
Carbon monoxide – CO	14-70 m^3/h	From 20 000 broilers	Canadian Poultry, 2012
Carbon dioxide – CO_2	0.17-0.52 kg/year	From one-layer hens	Broucek, 2018; AgroTech, 2011
	0.68-2.94 kg/year	From one broiler	
$PM_{2.5}$ dust	0.0008 kg/year	From one broiler	Bip, 2020
PM_{10} dust	0.004-0.025 kg /year	From one broiler	

The total amount of ammonia (NH_3) released from poultry manure from laying hens ranges from 2 to 20%, and from broilers from 13-20% (Ross et al., 2020; Dróżdż et al., 2020). Also, high levels of ammonia of above 25 ppm in a poultry house can cause decreased appetite in animals, slower weight gain, generated the oxidative stress, respiratory problems, aches and pains, and inflammation of the eyes (Swelum et al., 2021).

Storing by-products from poultry breeding, i.e., poultry manure, also generates a loss of ammonia to the atmosphere and soil. Storage of poultry manure on the farm in an uncovered area generates losses of 21% NH_4-N, while covered manure loses only 13% of NH_4-N. However, to reduce losses of storing manure in closed containers/facilities is recommended. This can reduce these losses to 11% of NH_4-N. Total nitrogen loss from poultry manure storage ranges from 13 to 30%. Depending on the season, a storage method, poultry breed, nutrition, and external factors, such as temperature and humidity (Chastain et al., 1999).

Microplastics

Microplastics are a mixture of particles of different shapes derived from plastics which range in size from 0.1 µm to 5 mm (Wu et al., 2021). The sources of microplastics are plastic products which production exceeded 350 million tons worldwide in 2018 (Report on Use of Plastics in Agriculture, 2019). Microplastics are pollutants that can appear in the soil because of fertilization with e.g., mineral fertilizers, fresh animal manure, dry manure, compost, etc. As they migrate deeper into the soil profile, microplastics can lead to permanent damage. The mobility of microorganisms in the soil is disturbed, resulting in the immobilization of genes responsible for antibiotic resistance. Microplastics also disrupt carbon, nitrogen and phosphorus fixation cycles and affect the physical and chemical properties of the soil. However, it must be emphasized that still there are no conclusive studies determining what diseases in humans and animals can be caused by microplastic exposure from food, air or water and what dose of microplastic is toxic to the body. Contamination with microplastics has been considered a pressing issue now and has been studied by the scientists around the world only for a decade (DOZ, 2021).

Statistics demonstrate that the microplastics content in soil is at least 4 to 23 times higher than in the oceans. Plastics that produce microplastics include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polycarbonate (PC), polyamide (PA), and polyethylene terephthalate (PET) (Wu et al., 2021).

On poultry farms, microplastics can be found in feed, litter, air, and in poultry manure and urine. For example, it comes from bowls, bags, pipes, bottles, and other items made of plastic. Over time, these items degrade, resulting in the formation of microplastics. Then, a large quantity of them ends up in manure, which is often used as a fertilizer. One of the first articles to show and compare microplastic content was published in 2021 and focused on the China area. Wu et al, (2021) were reported the highest amounts of the polypropylene, polyethylene and polyethylene terephthalate were identified in manure and animal feed. The researchers also found that organic fertilizers based on animal manure can affect the transport of microplastics to soil, water, and the atmosphere. As a result, microplastic from poultry manure can contribute to environmental pollution. To prevent, farmers should pay more attention to what materials they use in animal husbandry. Farmers should reduce the use of plastics in preference to biodegradable and compostable materials. Although these materials are often expensive, but biodegradable/compostable products are considered environmentally friendly (Wu et al., 2021).

2.4. Methods for processing of poultry manure

Significant quantities of poultry manure generated on poultry farms need to be handled and managed efficiently. Long term storage of poultry manure causes loss of valuable plant nutrients. From solid poultry manure, deep litter, or litter, it is estimated that 25 to 50% of nitrogen, 5 to 15% of P_2O_5, and 5 to 15% of K_2O are lost (Hansen, 2006; Ross et al., 2020).

Poultry manure should be stored in a dry place, protected from excessive rainfall, in floodplains, near water reservoirs, etc. (Hansen, 2006; Breeding.eu, 2017).

In Poland, poultry manure is mainly applied in unprocessed form, spread directly on agricultural land as a high source of nitrogen. Poultry manure is particularly important for root crops (i.e., potatoes, sugar, and fodder beets) and corn. Farmers usually apply manure in fall, near the end of crop vegetation, on a 3- and 4-year cycle. The Regulation of the Minister of Agriculture and Rural Development of June 18, 2008 on the implementation of certain provisions of the Act on Fertilizers and Fertilization of 2007, indicates that organic fertilizers should be used in doses not exceeding 170 kg of N per hectare of crop.

The excess poultry manure can be turned into added value products and energy, which can be sold on the market. The minimum price for poultry manure in Poland, in 2021-2022 was 11 EUR/Mg and the maximum price was 15 EUR/Mg (Economics, 2022). Buyers of poultry manure, use it mainly for growing media for mushroom growth.

Poultry manure can be used as a substrate for anaerobic digestion and biogas production. It is also processed into an animal feed additive (Augustyńska-Prejsnar et al., 2018). Poultry manure can be mixed with selected bulking agents e.g., wheat straw or wood chips, for obtaining valuable compost. Poultry manure can be used for energy purposes, i.e., biomass energy of poultry manure, combustion of poultry manure can provide heating for poultry houses, co-incineration, possibility to use poultry manure for combustion separately or with gas-fired coal, combustion of poultry manure in fluidized bed furnaces, gasification, and synthesis gas production (Myszograj et al., 2012; Wieremiej, 2017; Augustyńska-Prejsnar et al., 2018). Poultry manure is also subjected to the pelleting process. The pelletization process can be modified by adding substrates that will improve the density and properties of the resulting pellets. The finished pellets can be combusted to recover energy which can be used for space heating. Pellets can also be used as feed additives and as fertilizer. The potential use of poultry manure can also include the production of biochar by pyrolysis in the temperatures of 200-700ºC. Temperature has a significant effect on the properties of the produced biochar (Mid-Atlantic, 2006; Tańczuk et al., 2019; AgroProfil, 2020; Dróżdż et al., 2020 Sobik-Szołtysek et al., 2021).

The literature provides numerous examples of poultry manure applications in various thermal, chemical, and biological processes (Table 12).

Table.12. Overview of various methods for poultry manure management.

	Substrate	Methodology	Application	References
Category: **Drying**				
1	**Substrate:** Poultry manure from 2 years old chickens	**Temperature:** a) First Drying in 100°C, b) Second drying in 50°C, c) Open room with 22°C. **Time:** 48h, **Process**: in electric oven, **Nutrients:** Before drying was 1.87% of N, after drying in 100°C was 1.62% N, in 50°C was 1.67%N, and 1.7% N in 22°C.	This is one of the oldest research papers on poultry manure. The authors dried poultry manure to check the scale of nitrogen losses. It turned out that $^{1}/_{10}$ of the manure nitrogen is lost by drying.	Buckner et al., 1926
2	**Substrate:** Poultry manure	**Temperature:** 40°C and 60°C **Process:** The material was distributed to a thickness of 1 and 3 cm before drying. **Nutrients:** The protein content dropped from 43% to 39-41%. At 60 ° C, there was the greatest reduction of bacteria of the genus *Escherichia coli* and *Salmonella.*	The dried poultry manure proved to be safe and, in terms of nutrient content, suitable as a feed ingredient for (ruminant) animals.	Ghaly et al., 2012
3	**Substrate:** Poultry manure	**Temperature:** 60°C **Process:** Drying the poultry manure resulted in the reduction of unpleasant odors, i.e., ammonia. **Nutrients:** Reduction of the N:P: K ratio from 4.58: 1.29: 1 to 2.57: 1.28: 1.	Dried poultry manure can be used as fertilizer for plants. Due to the high content of nitrogen, phosphorus, and carbon.	Ghaly, et al., 2013
4	**Substrate:** Poultry manure	**Process:** Poultry manure drying installation using a belt process. With the use of a furnace, fans, and drainers.	Utilization of unpleasant odors and the possibility of further utilization of the dried poultry manure.	Bao et al., 2020
Category: **Pelletizing**				
5	**Substrate:** Poultry manure	**Drying temperature:** 95°C, **Process:** granulation with mineral additives, i.e., potassium chloride and diammonium phosphate. **Nutrients:** NPK (4-4-2, 4-3-6 and 4-4-9).	The use of about 2 tons per ha of granules had a positive effect on the growth of rape and potatoes.	Mazeika et al., 2016
6	**Substrate:** Poultry manure from poultry litter	**Process:** The feed mixture contained 20% and 40% pellets from poultry bedding.	The use of granules as an additive to goats feed (protein source). The mixtures positively influenced the growth of animals.	Jackson et al., 2006

7	**Substrate:** Poultry manure	**Process**: To produce pellets, rice straw and poultry manure were mixed.	The poultry manure content ranged from 26 to 80%. The more poultry manure in the pellet, the harder the pellets formed.	Zdanowicz & Chojnacki, 2017
8	**Substrate:** Poultry litter	**Process:** 6.7 Mg/ha of granules went into the soil. **Nutrients:** N_{tot}= 221 kg/ha C_{tot}= 2000 kg/ha	A positive effect on cotton growth was observed when poultry litter pellets were added to the soil.	Feng et al., 2019
Category: **Anaerobic digestion**				
9	**Substrate:** Poultry manure from laying hens	**Temperature:** Incubation in 35°C. **Process:** Methanogenesis was correct, up to the concentration of ammonia not exceeding 250 mg/l.	The efficiency of converting organic nitrogen to ammonia during fermentation was 60 to 80%.	Bujoczek et al., 2000
10	**Substrate:** Poultry and pig manure	The proportions are 24% poultry manure and 76% pig manure. **Process:** The process temperature was 90°C and the pH was 10.	The high temperature made it possible to remove nitrogen from the mixture at the level of over 70%. Pre-treatment resulted in 1.2 times higher methane production.	Rodriguez-Verde et al., 2018
11	**Substrate:** Poultry manure from cage breeding, mixing with 5% of biochar	**Temperature:** 35°C, **Process:** Fermentation lasted 72 days. The process is carried out in a 500 ml vessel with a working volume of 400 ml.	Biochar obtained at 550°C from fruit trees allowed to increase the efficiency of methane production by 69% from poultry manure.	Pan et al., 2019
12	**Substrate:** Poultry litter	**Process:** Potential to use leachate from anaerobic digestion with poultry manure and algae *Chlorella minutissima*, *Chlorella sorokiniana* and *Scenedesmus bijuga*.	Substantial production of biomass that can be used as an animal feed additive.	Singh et al., 2011
Category: **Composting**				
13	**Substrate:** Poultry manure from cage breeding	**Process:** Poultry manure, straw, and biochar at a dose of 0-10% were used for composting. The biochar was made of wheat straw and coconut shells at a temperature 500-600°C.	The use of the addition of biochar had a positive effect on the metabolism of toxic microorganisms.	Awasthi et al., 2021
14	**Substrate:** Poultry manure with straw and the addition of bamboo biochar	**Process:** Composting was carried out for 42 days. 2.5-10% biochar made from bamboo was added to the compost mixture.	The addition of 10% biochar allowed the most effective reduction of nitrogen losses during composting.	Awasthi et al., 2020

15	**Substrate:** Mixture of poultry manure and olive oil mill waste	**Nutrients:** The obtained compost with parameters C/N 19, pH 9.27, ammonia content 0.15 g/kg.	The use of compost in particularly saline soil allowed for the growth of plants with shoots resistant to the influence of salt.	Walker et al., 2008
16	**Substrate:** Poultry manure with corn straw	**Process:** The maximum temperature that was reached was 68°C. The composting process was completed after 60 days.	Additional microorganisms (ie *Bacillus*, *Aspergillus* and *Trichoderma*) were added to the compost. Placing the inoculum reduced the ammonia content and accelerated the composting process as well as improved material humification.	Wan et al., 2020
Category: **Pyrolysis**				
17	**Substrate:** Poultry manure from young hens	**Temperature:** The biochar was produced at the temperatures of 350, 450 and 600°C. Heating times 30, 60, 90 and 120 minutes.	The obtained biochars at lower temperatures were more chemically stable than those at high temperatures.	Cimò et al., 2015
18	**Substrate:** Poultry manure	**Temperature:** The biochar was produced at 350 and 700°C.	The addition of biochar to the soil increased the pH from 4.8 to 6. Poultry biochar, which was formed at 350°C, had the least impact on the soil pH.	Hass et al., 2012
19	**Substrate:** Poultry litter	**Temperature:** Production of biochar from poultry litter, which has been processed into bio-crude oil before being used for pyrolysis. The process took place at 450, 500 and 550°C.	The obtained biochar ash was rich in phosphorus, potassium, calcium, and magnesium.	Agblevor et al., 2010
20	**Substrate:** Poultry litter	**Process:** Slow pyrolysis took place at 600°C. Poultry litter and pine biomass were used to produce biochar.	Higher ash and protein content was noted, which came from the poultry litter. The addition of pine biomass inhibits the growth of microorganisms, while the addition of biochar from the poultry litter accelerates the growth of microorganisms.	Das et al., 2008
Category: **Other**				
21	**Substrate:** Poultry manure	**Process:** Media for fungi, i.e., mushrooms. Sawdust, rice husks, wood shavings, and straw are desirable in poultry litter.	It is a source of nitrogen for fungi. Poultry manure is cheaper to buy than chemical products.	Mushrooms Solutions, 2019

22	**Substrate:** Poultry manure from broilers and laying hens	**Process:** The manure was applied to dusty, light soil. After manure was placed on the soil, it was covered with wind tunnels to monitor ammonia loss.	On average, about 50% of ammonia evaporated from the manure placed on the soil. Re-wetting the soil increased emissions of ammonia. It also turned out that almost 20% of the emissions were recorded in the first 4.5 hours of placing fresh manure on the soil.	Miola et al., 2014
23	**Substrate:** Poultry manure	**Process:** Generation of energy from the combustion of poultry manure. Combustion in a fluidized bed.	Generation of energy from combustion, which can be used for heating farms, generating electricity through a cogeneration system. Thus, will be reducing ammonia emissions from farms.	FarmersWeekly, 2019
24	**Substrate:** Poultry litter	**Process:** Poultry feed additive. First, the poultry litter was composted. Then the finished compost was dried, and the shredded material was used as a feed additive.	The composting process will reduce pathogens in fresh poultry manure.	PPR, 2002
25	**Substrate:** Poultry manure	**Process:** Addition of poultry manure to the production of Portland cement.	Using less than 25% of poultry manure preserves the binding properties of the cement.	Sobczak, 2008
26	**Substrate:** Poultry manure	**Process:** Gasification of poultry manure from which syngas is produced.	Production of synthesis gas was a lower calorific value of 2 MJ/m^3 from raw, dried poultry manure than from poultry pellets at 2.7 MJ/m^3.	Tańczuk et al., 2019
27	**Substrate:** Poultry manure	**Process:** Landspreading of dried poultry manure on fields.	It is mainly used for fertilizing cereal crops. In a dose not exceeding 170 kg N/ha.	Loyon, 2018

The use of poultry manure in the literature is confirmed by numerous scientific publications. It is a substrate with a wide spectrum of possibilities and potential ways of management.

Research on poultry manure began as early as the 1920s. One of the first available publications is a 1926 article written by Davis Buckner G. and Peter A.M., published in Poultry Science. The article focused on nitrogen losses from dried poultry manure on a poultry farm in Kentucky (USA). The researchers found that the higher the drying temperature, the higher the nitrogen losses (Davis Buckner & Peter, 1926).

Practice case studies on poultry manure in Poland

In Poland, most of the poultry manure is used as fertilizer for crops, especially root crops (beets and potatoes), corn and canola. These plants are tolerant to high levels of nitrogen more than other crops. Their yield is also highest when chemical fertilizers are applied (Agroprofil, 2020). Poultry manure contains about 15 kg/t N, 15 kg/t P, 4 kg/t K, and 24 kg/t Ca. Farmers apply raw poultry manure and liquid fraction from poultry manure mainly in the autumn and spring (IUNG, 2000; Rural News, 2017; Agroprofil, 2020).

Another example of the practical use of poultry manure is to convert it into thermal energy to heat poultry houses or other outbuildings. The company BHLS was one of the first companies in Poland which engaged in combusting poultry manure in a fluidized bed. Combustion of poultry manure in the fluidized bed generated heat and electricity, which was used in the poultry house. Combustion was performed in Fluidized Bed Combustion - FBC (BHLS, 2015). Converting poultry manure into energy through combustion is not the only technique used by companies in Poland. Biogas plants are increasingly turning to poultry manure as a substrate for biogas energy production, as well as a fertilizer from anaerobic digestion residues. In addition, poultry farms are looking for new energy solutions to replace traditional coal-fired energy sources. In addition, by 2030 Poland must minimize the use of coal and choose alternative sources of the energy, especially for heating poultry houses. Also, the use of poultry manure substrate in a biogas plant will reduce production costs incurred by farms. An increasing number of companies are appearing on the Polish market with solutions that improve the fermentation process. Poultry manure is a difficult substrate to use in a biogas plant, due to it is high nitrogen content, which limits or inhibits the methane bacteria that produce biomethane. However, companies are appearing on the market that can utilize up to 70% of the feedstock consisting of poultry manure. The companies combine an evaporation system (evaporation of ammonia and water from the poultry manure) with nitrogen extraction (obtaining ammonium sulfate, which can have further use as fertilizer). Poultry manure prepared in this way can be used in methane fermentation without disturbing the biochemical transformation processes of microorganisms (Biomass, 2016; BotresGlobal, 2021).

Another way to manage excess poultry manure is to pelletize. Various types and sizes of pelletizers are available on the market that produce pellets, for combustion, for energy, for fertilizer purposes, and as a feed additive (FDSP, 2018). However, there is insufficient information in the available literature on the practical use of the poultry manure biochar in Poland.

2.4.1. Pyrolysis of poultry manure

Poultry manure can be thermally converted through pyrolysis to obtain biochar which in turn can be used as a soil enhancer (Kelleher et al., 2002; Zhao et al., 2018; Czekała et al., 2019). According to the European Biochar Certificate (EBC), biochar is defined as a carbon material resulting from the pyrolysis of plant or animal biomass. Biochar can absorb carbon in the long term due to its porous and intense sorption properties.

Pyrolysis is a process of thermal conversion of various substrates without oxygen (Wystalska et al., 2018). Poultry manure derived biochar can be potentially applied as a composting additive limiting gaseous emissions (Chung et al., 2021), as a sorbent for e.g., immobilization and/or removal of heavy metals or other contaminants (Sobik-Szołtysek et al., 2021), a soil improver (Mierzwa-Hersztek et al, 2016), and as an additive to carbon sequestration (Wystalska et al., 2018).

Physicochemical parameters of biochar from poultry manure

Depending on the pyrolysis temperature and the type of poultry manure, biochar is characterized by the following parameters, i.e., pH 7.20-10.5, C 33-86%, H 0.3-5.6%, N 0.12-4.9%, S 0.4-3.5%, O $<$0.01-42%, Na 1.5-2.9%, P 1-9.1%, CEC 29-86 cmol/kg (Wystalska et al., 2018; De Bhowmick et al., 2018; Li and Chen, 2018; Bavariani et al., 2019; Bavariani et al., 2019; Bavariani et al., 2019). The elemental composition of the biochar, specific surface area, pH, porosity and nutrient content, stability and function of the surface groups can be modified by the temperature of the process (Li et al., 2017; Hasnan et al., 2018; Zhao et al., 2018; Li and Chen, 2018; Manyà et al., 2018).

Due to the fact that the biochar can contain various contaminants such as heavy metals, furans, dioxins, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons, it has to fulfill the requirements of the permissible limits if applied to the soil (Hibler et al., 2012; Fabbr et al., 2013; Malińska et al., 2016). In Poland, these requirements are defined in the Regulation of the Minister of Agriculture and Rural Development, Act on Fertilization and Fertilizer (2008). Biochar produced from poultry manure is also an alternative to use as a soil enhancer (Kelleher et al., 2002; Zhao et al., 2018; Czekała et al., 2019). Poultry manure derived biochar can have several potential applications. It can be used as an additive limiting gaseous emissions during composting, a biofilter, as a material/a sorbent for the immobilization of heavy metals and other contaminants, a soil enhancer and as an additive to carbon sequestration (Wystalska et al., 2018; Dróżdż et al., 2020; Wystalska et al., 2021; Sobik-Szołtysek et al., 2021; Agbede and Oyewumi, 2022). Table 13 presents the examples of benefits and limitations from pyrolysis process.

Tab.13. Benefits and limitations from pyrolysis process.

No.	Process temperature	Substrate	Benefits	Limitations	References
1	300-600°C	Poultry manure+ corn straw, pine sawdust	Due to its high ash content, the resulting biochar has very high sorption properties for organic pollutants.	The higher the process temperature, the higher nitrogen and carbon losses in the obtained biochars.	Li et al., 2018
2	425-725°C	Poultry manure	Biochar produced at 575°C showed the highest sorption properties for metals, i.e., Zn, Cd and Pb, from aqueous solution.	High pH above 10 can be undesirable when biochar is used as soil enhancers.	Sobik-Szołtysek et al., 2021
3	550-600°C	Poultry manure	Reduction of greenhouse gas and ammonia emissions. Biochar in the compost mixture helped accelerate the maturation of the compost.	Not specified in the article.	Chen et al., 2020
4	350-600°C	Poultry manure	The chemical composition of biochar depends on the temperature of the process and not on the time of pyrolysis.	Biochar from the temperature of 600°C is less stable in terms of aromatic domains than those produced at low temperatures.	Cimò et al., 2014
5	400-500°C	Poultry litter	The possibility of using the obtained biochar as soil enhancers.	High construction costs of a low-temperature pyrolysis installation.	Słodeczek and Głodek-Bucek, 2017
6	500°C	Poultry manure	Biochar had a positive effect on copper uptake in soil, which is toxic to plant growth.	Not specified in the article.	Meier et al., 2017

Through a review of the literature, it is found that regardless of the pyrolysis substrate used, the physicochemical properties of the obtained biochar depend mainly on the process temperature. The obtained biochar is characterized by high sorption properties, which are useful when absorbing, for example, heavy metals from the soil. However, a major limitation to the large-scale use of pyrolysis is the high cost of installation and energy consumption (Agbede and Oyewumi, 2022).

2.4.2. Composting of poultry manure

Composting is defined as organic recycling that proceeds under aerobic conditions (Haug, 1999). According to Act from December 14, 2012, about waste, organic substrates composted in controlled process conditions undergo biological decomposition have several microorganisms support the process of composting. Composting of poultry manure reduces odors and can help reduce the decreased number of pathogens (Kreidenweis et al., 2021). Composting is one of the most common processes for obtained soil enhancers which is used in horticulture and for domestic use. Beneficial effects of compost on soil properties and plant growth have been reported in numerous studies (Martínez-Blanco et al. 2013; Cesaro et al. 2015; Alsanius et al. 2016; Oliveira et al. 2017; Hu et al, 2017, Ansari et al., 2019; Lori et al., 2022).

Phases and requirements for the composting process

The composting process consists of 4 phases, including mesophilic, thermophilic, cooling, and curing phase (i.e., compost maturation) (Haug, 1999). The most common microorganisms during the composting process include fungi such as *Aspergillus, Chrysosporium, Fusarium, Mortierella, Penicillium, Acremonium*, and *Trichoderma.* The fungi dominate mainly in the initial and final phase of composting when the temperature does not exceed 30-40°C. Also, bacteria, are a numerous group during the process, for example *Bacillius, Clostridum, Pseudomonas and Xanthomonas, Actinobacteria* and *Nitrosomonas and Nitrospira* (Sanchez et al., 2017; Awasthi et al., 2021).

The following parameters are required for composting process, the content of organic matter (>60 %), moisture content (40-65 %), C/N (20-40:1), pH (5.5-9), temperature for proper hygienization (43-70°C) and oxygen concentration (>5 %). Poultry manure can be mixed with a variety of plant agricultural residues. Due to high moisture and nitrogen content poultry manure should be mixed with suitable bulking agents to achieve the required moisture content, C/N ratio and porosity of the composting mixture. Typical bulking agents include various types of straw, sawdust, grass, or wood chips (Rynk, 1992; Haug 1999, Umaine, 2016, Dróżdż et al., 2020). Table 14 presents the benefits and limitations in the composting process.

Tab.14. Benefits and limitations in the composting process.

No.	Days of composting	Type of composting	Substrate	Benefits	Limitations	References
1	42	Composting reactor	Poultry manure+ wheat straw+biochar willow woodchips	Biochar in the composting of poultry manure and straw has helped reduce ammonia emissions about 30-40% and increased the C/N ratio.	Composting temperature above 75-80°C can cause abiotic oxidation of biochar and, consequently, its microbiological degradation.	Janczak et al., 2017
2	28	Windrow composting	Poultry droppings+ dried cassava peels	The compost obtained had a high nutrient content.	The obtained temperature of 31°C cannot be sufficient to hygienize the compost from poultry manure.	Ojo et al., 2018
3	40	Composting reactor	Poultry manure	The obtained compost from poultry manure was stable and mature, ready to be used as a soil improver.	High ammonia and carbon dioxide emissions from composting only poultry manure.	Rizzo et al., 2022
4	50	Composting reactor	Poultry manure+ corn straw	Poultry manure can be composted properly even under high stress caused by heavy metals.	Heavy metal loading can result in slower degradation of organic matter by microorganisms that must adapt to stressful conditions.	Chen et al., 2022
5	42	Composting reactor	Poultry manure+ wheat straw+biochar from poultry manure	The addition of biochar from poultry manure to the compost mixture resulted in the reduction of greenhouse gas emissions and ammonia. The addition of biochar from poultry manures also had a positive effect on the faster degradation of organic matter.	Composting poultry manure with straw generates significant emissions of greenhouse gases and ammonia compared to compost mixtures with the addition of biochar.	Chen et al., 2020
6	42	Composting reactor	Poultry litter+vinegar residue+lime+biochar	Reduction of ammonia, carbon dioxide and nitrous oxide emissions.	Increasing the electrical conductivity at the beginning of the composting process slowed down the growth of bacteria and fungi. The thermophilic phase of composting has also been delayed.	Liu et al., 2022

In summary, composting is a simple process of converting organic waste into a full-value product such as compost. The produced compost derived poultry manure has fertilizing potential, which has a positive effect on soil properties and plant growth. However, the challenge that occurs during the process of composting is gaseous emissions which are a nuisance and negatively affect to the environment where the process is carried out. Adding a bulking agent with high sorption properties, such as biochar, to the compost mixture can reduce significant gas emissions.

The carbon (C), phosphorus (P) and nitrogen (N) cycle during the process of composting

During composting, organic matter decomposes, resulting in gaseous emissions such as ammonia. Water evaporates during the process, resulting in leachate. The condensate, in comparison to the leachate, is mainly formed in closed composting systems. The composting process is performed in composting reactors (Haug 1999; Caceres et al., 2018). A simplified scheme of the changes occurring during the windrow composting is presented in Figure 2. The scheme also demonstrated the cycling of the elements C, N and P.

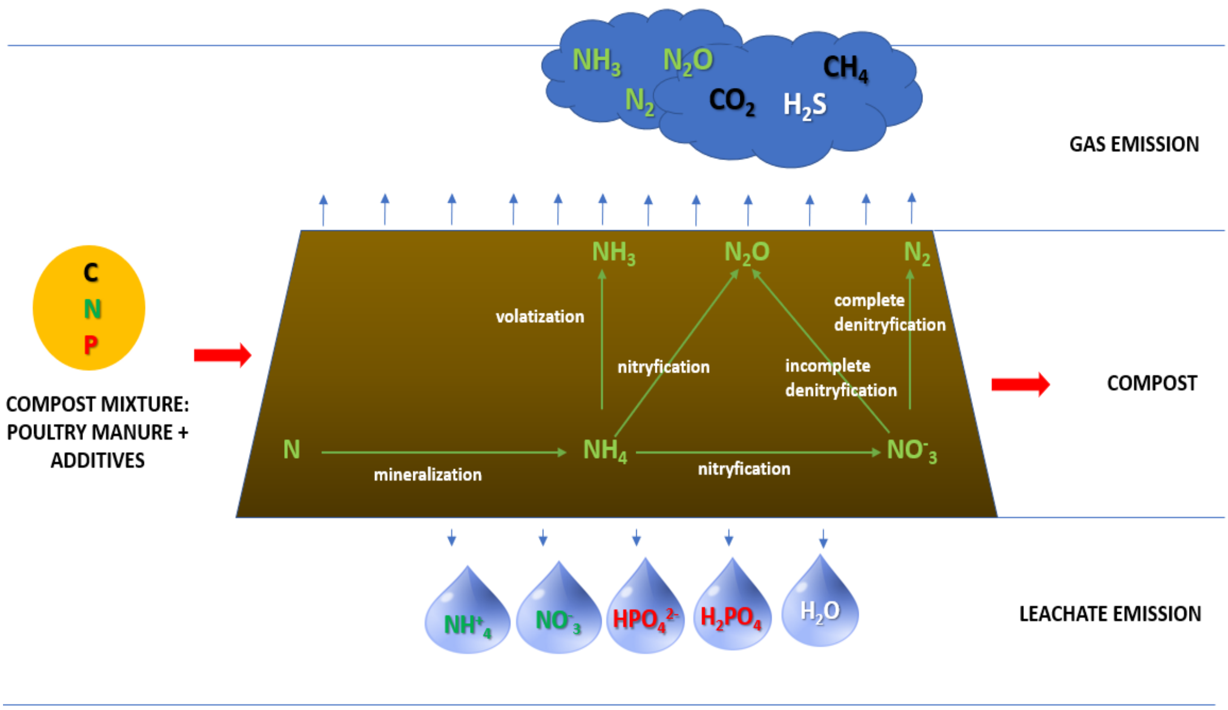

Fig.2. The carbon (C), phosphorus (P) and nitrogen (N) cycles during the process of composting (Caceres et al., 2018; Ross et al., 2020).

The quantities of produced gases during composting generally depends on the composting mixture composition with bulking agents (i.e., C/N, MC, OM, pH, EC, nutrient content, aeration) (Caceres et al., 2018). Also, gaseous emissions are influenced by the method of composting (windrow composting or in a composting reactor) (Ross et al., 2020). It is reported that when poultry manure is composted, significant amounts of gases are released (Amanullah et al., 2007; Janczak et al., 2016; Czekała et al., 2017; Caceres et al., 2018; Ross et al., 2020).

Loss of nitrogen during composting poultry manure are mainly in the form of NH_3, ranges from 13-70% (Tiquia et al., 2002; Amanullah et al., 2007; Harisson et al., 2008; Ross et al., 2020). The NH_3-N is very quickly converted to gas and released from the poultry manure composting process when the pH is between 8.4 and 9.0 and the process temperature reaches 65-70°C (Chowdhury et al., 2014; Caceres et al., 2018). Nitrogen in poultry manure is transformed during composting from NH_4^+ oxidized to NO_2^- and, to NO_3^- by nitrification, and ammonification (from organic N to NH_4^+). In the composting process also NO_3^- is transformed into N_2 through denitrification (Wang et al., 2015; Caceres et al., 2018). Nigussie et al., (2016) estimated the total N loss from the composting process of organic waste is from 40 to 70%, mainly in the thermophilic phase. N is released from composting mainly as NH_3, NO_x, N_2O and N_2.

Loss of carbon during composting poultry manure are mainly in the form of CO_2 and CH_4 estimated between 42-62%. Losses of carbon depend on the ratio of the mixture of manure, the type of and the phase of the process (Harisson et al., 2008; Ross et al., 2020). The CO_2 emissions from hen poultry manure applied to soils were approximately 800 mg/kg while from broiler poultry manure was about 600 mg/kg (Martin et al. 2012).

The reduction of phosphorus during composting poultry manure are mainly in the form of HPO_4^{2-} and H_2PO_4 and can be in the range of 28-50% (Tiquia et al., 2002; Harisson et al., 2008). From 12 to 20% of the phosphorus in poultry manure is readily soluble in water. When the phosphorus in poultry manure is mixed with soil, also can be easily leached from the soil (Guo et al., 2009).

Losses of nitrogen, carbon, and phosphorus are quite problematic for the composting process, especially for animal manure such as poultry manure. In the literature, it is possible to find methods and bulking agents for reducing losses of nutrients and gases during the process. The methods and bulking agents used also have a positive effect on the process parameters and the properties of the produced compost. Table 15 provides examples of substrates that reduce nitrogen, carbon, and phosphorus losses.

Tab.15. Examples of substrates that reduce nitrogen, carbon, and phosphorus losses.

No.	It reduces loss of	Loss reducing substrate	Influence for composting process	References
1	Ammonia	Biochar from willow woodchips.	The addition of biochar (5% and 10% dose) to the composting process of poultry manure with straw had a positive effect on reducing ammonia losses by 33% and 44%.	Janczak et al., 2017
2	Nitrogen	Microbial Nitrogen Retaining Factor (NRMA).	Composting poultry manure with rice husks and the addition of NRMA, reduced ammonia losses by 58.8% with a 15-day composting cycle. In the compost with NRMA, total nitrogen and nitrates were higher than in the compost without the addition of NRMA by 23.3 g/kg and 4.5 g/kg.	Qiu et al., 2021
3	Nitrogen	Zeolite	Zeolite in a dose of 10% reduced nitrogen losses and lowered the salinity of the compost.	Chan et al., 2016
4	Nitrogen	Sulphur and *Thiobacillus thioparus* 1904.	Sulfur and *Thiobacillus thioparus* 1904 affect the expression of genes encoding nitrogen-related proteins. The combination of sulfur and *Thiobacillus thioparus* 1904 reduces nitrogen losses (44% reduction) during the composting of poultry manure.	Lu et al., 2018
5	Ammonia and nitrous oxide	Biochar and zeolite.	The use of 10% biochar and 10% zeolite reduced ammonia loss by 63.4% and nitrous oxide by 78.13% in the composting process for pig manure and wheat straw. The use of biochar and zeolite additionally limited the mobility of heavy metals and accelerated the humification of organic matter.	Wang et al., 2017
6	Methane, nitrous oxide, and ammonia	Phosphogypsum and superphosphate.	Phosphogypsum and superphosphate at 10% reduced methane emissions by 85% and 80% during composting of kitchen waste. Ammonia emissions were reduced by 23% and 18.9%. Whereas nitrous oxide emission slightly increased by 3.2% and 14%. The use of phosphogypsum and superphosphate reduced total greenhouse gas emissions by 17.4% and 7.3%, respectively.	Yang et al., 2015
7	Methane, nitrous oxide and ammonia	Bamboo biochar and powdered bacteria such as *Firmicutes* and *Proteobacteria.*	The addition of bacteria and biochar allowed to reduce emissions from composting pig manure, methane by 54-80%, nitrous oxide by 37-45% and ammonia by 13-26%.	Mao et al., 2018

8	Methane, ammonia, and carbon dioxide	Substrate A (sulphates and oxides of iron, magnesium, manganese, and zinc mixed with clay) and substrate B (mixture of calcium hydroxide, peroxide, and oxide).	During the composting of plant waste with peat and substrate A and B, the content of ammonia dissolved in water decreased and the content of nitrates increased. Substrates A and B also reduced the carbon dioxide content.	Himanen and Hanninen et al., 2009
9	Carbon	*Bacillus subtilis*	The addition of *Bacillus subtilis* to the compost mix at a dose of 2% resulted in the retention of 0.5% more organic carbon in the mix compared to the control without the addition of bacteria.	Duan et al., 2020
10	Phosphorus	Manure	Animal manure composting increases the total phosphorus content by 10 to 55% compared to slurry.	Kumaragamage et al., 2018
11	Phosphorus	Fresh poultry litter	The addition of fresh poultry litter to the compost mixture increased the content of phosphorus available for plants by 60-140 mg/kg.	Preusch et al., 2002
12	Phosphorus	Oak tree biochar	Composting poultry manure with green waste and biochar resulted in a 10% increase in available phosphorus.	Vandecasteele et al., 2013

Composting poultry manure is an alternative to managing the excessive amounts that are generated on poultry farms. However, the process of composting poultry manure itself is difficult due to maintaining the proper C/N ratio, aeration, temperature and avoiding excessive gas and leachate emissions. However, scientists are attempting to reduce gas emissions from composting by using bulking agents with high sorption properties, such as biochar, minerals (zeolite, gypsum, etc.) and bacteria.

Greenhouse gases, including carbon dioxide, methane, hydrofluorocarbons, sulfur hexafluoride, perfluorocarbons, and nitrous oxide, in Europe are 94% derived from agriculture. There has also been a 22% reduction in greenhouse gas emissions between 2019 and 1990 (Locja, 2022; PAP local government service, 2021).

2.4.3. Drying of poultry manure

The drying process is another method of managing poultry manure. Drying poultry manure reduces excess water and partially minimizes odors. This procedure reduces logistical costs associated with storage and transportation of poultry manure (Kic et al., 2013). During drying processes such as pure diffusion, surface diffusion, Knudsen diffusion, capillary flow, intense evaporation, condensation and thermodiffusion occur. It should also be considered that the dried material can shrink. The drying time depends on the thickness of the sample and the amount of moisture, as well as the parameters of the equipment used for drying (Vasić et al., 2012). Table 16 presents the benefits and limitations of dried poultry manure.

Tab.16. Benefits and limitations of dried poultry manure.

No.	Substrate (Type of drying)	Benefits	Limitations	References
1	Poultry manure (solar drying)	It can be used as a granular fertilizer. Drying also reduced the unpleasant smell of the poultry manure.	The pellet, which was created in the SFR machine, as a fertilizer with a slow release of nutrients, was a highly energy-consuming process compared to the production of SFR pellets.	Purnomo et al., 2017
2	Poultry manure (oven drying at 65°C)	Drying in the air at 22°C caused the content of P, Ca, and Mg to be much higher and the fractions more stable than in the poultry manure that was dried in the oven.	High drying temperature causes limitations in obtaining higher P, Ca, and Mg content from poultry manure.	Dail et al., 2007
3	Poultry manure (air drying in 22°C)			
4	Poultry manure (heated air-drying 60°C)	Drying reduced unpleasant odors, bacteria, and fungi.	During drying, the thickness of the drying layer is a key aspect, the thinner the drying is.	Ghaly et al., 2012
5	Poultry manure (oven drying 40-60°C)	Drying the manure caused the pH to drop from 8.4 to 6.6. unpleasant smell and aggressiveness of poultry manure decreased by 65-69%.	The higher the drying temperature, the higher the reduction of odors, bacteria, and fungi. It is also associated with higher energy consumption.	Ghaly and MacDonald, 2012
6	Poultry manure (oven drying 95°C)	The dried granulated poultry manure was used as a fertilizer for the growth of rape and potatoes. The use of 2 t/ha resulted in a significant difference in plant growth compared to the control (soil only).	High energy consumption for drying poultry manure. The energy consumption was 100 kWh/t.	Mazeika et al., 2016

Drying poultry manure at high temperatures can help reduce harmful microorganisms, reduce odor intensity, dry and simple to store (OZPZD, 2021). High temperature during drying >60°C reduces mold, yeast, bacteria such as *Escherichia coli* and *Salmonella*. According to Ghaly et al., (2012), drying the manure at 60-105°C allowed the reduction of 65-99% for mold, 74-99% for yeast and 99.97% for *Escherichia coli,* and 100% for *Salmonella*. After drying, poultry manure can be pelleted or pressed to produce pellets with fertilizer potential or used as substrate for combustion. Poultry manure in granular/pellet form is lightweight as 1 kg of dried poultry manure is equivalent to 4 kg of fresh manure (OZPZD, 2021).

2.5. Poultry manure derived biochar

Biochar from poultry manure has been investigated by scientists for use as a soil enhancer. Bavariani et al., (2019) analyzed biochar from poultry manure which was produced at temperatures between 300°C and 500°C. The researchers found that the higher the pyrolysis temperature, the higher the pH and salinity of the investigated biochar. High salinity can be detrimental to plants sensitive to significant salt concentrations in the soil. Highly saline biochar, for example, can be used on soils that are acidic. Masud et al., (2020) studied the effect of poultry manure biochar on improving soil acidity. The application of biochar resulted in the increase of soil pH. The organic matter contained in poultry manure biochar enabled the effective growth of maize compared to the control trial without biochar.

Mierzwa-Hersztek et al., (2016) analyzed poultry manure biochar for the soil enzymatic activity, toxicity, and plant growth. The researchers demonstrated that the application of biochar from poultry manure reduced soil acidity and increased carbon and nitrogen content. There were also no toxic effects of biochar on plant growth or microbial activity.

The pyrolysis temperature of poultry manure is important for biochars obtained for sorption applications, e.g., of pollutants such as heavy metals. For example, Agbede and Oyewumi (2022) conducted a study on the use of poultry manure and poultry manure derived biochar as soil enhancers for crops grown in degraded tropical soils. The incorporation of poultry manure and poultry manure derived biochar into the soil decreased soil bulk density and increased soil porosity and sorption capacity.

Sobik-Szołtysek et al., (2021) tested the effect of pyrolysis temperature on the heavy metal absorption properties of poultry manure derived biochar. The analyses demonstrated that the biochar presented adsorption properties towards heavy metals. Biochar obtained at 575°C can function as a sorbent for Zn. The biochar produced at 725°C can be used as a sorbent for cadmium. Wystalska et al. (2021) also reported that the temperature of pyrolysis affects the physicochemical properties of biochar from poultry manure. Meier et al., (2017) tested the potential of poultry manure derived biochar for reducing copper in copper-contaminated soil. Biochar from the poultry manure reduced the mobility and bioavailability of copper in the soil. Increased nutrient content also affected the plant growth.

Chung et al., (2021) conducted a study on reducing gas emissions and pathogen in composting process using biochar from poultry manure. The addition of 10% biochar reduced emissions of greenhouse gases, ammonia, and some pathogens. Biochar had a positive effect on the structure and water absorption of the compost. Phytotoxicity tests showed that the application of biochar allowed more than 90% of the cress to germinate.

A summary of fertilizing properties of biochar produced from poultry manure is presented in Table 17.

Tab.17. Properties of biochars derived from poultry manure.

Parameters		Temp.	Ash	pH	C/N	C	N	Na	P	K	S	Ca	Cu	Mn	References
Units		°C	%	-		%									
1	Poultry manure	580	8.32	7.86	65.5	55.7	0.85	0.21	0.38	1.92	0.10	4.63	0.013	0.068	Agbede et al., 2020
2	Poultry manure	580	0.028	7.56	80.5	52.3	0.65	0.21	0.73	1.25	0.091	0.75	0.013	0.065	Adekiya et al., 2019
3	Poultry manure	425	52.07	10.4	-	37.98	4.81	-	3.65	4.93	0.83	12.7	0.012	-	Sobik-Szołtysek et al., 2021
4	Poultry manure	575	61.74	10.65	-	36.22	2.5	-	3.28	4.47	0.88	16.3	0.009	-	
5	Poultry manure	725	78.38	12.45	-	37.42	2.76	-	4.00	5.55	1.09	18.1	0.012	-	
6	Poultry manure	550-600	-	9.32	75.16	-	0.45	-	-	-	-	-	-	-	Chen et al., 2020
7	Poultry litter	550	7.69	7.69	-	33.7	3.81	-	-	-	0.4	-	-	-	Qi et al., 2017
8	Poultry manure	200	-	7.20	-	39.7	3.53	-	3.39	1.044	-	-	-	-	Bavariani et al., 2019
9	Poultry manure	300	-	7.30	-	42.4	3.80	-	4.13	1.259	-	-	-	-	
10	Poultry manure	400	-	9.98	-	47.9	4.70	-	5.58	1.716	-	-	-	-	
11	Poultry manure	500	-	10.50	-	55.1	4.50	-	6.38	1.970	-	-	-	-	

Biochar can be used for soil remediation, as a sorbent for heavy metals and organic pollutants, as a liming and deacidifying compound and to reduce gas emissions (Srinivasan et al., 2015; Słodeczek and Głodek-Bucek, 2017; Li et al., 2018; Bavariani et al., 2019).

2.6. Poultry manure derived compost

Composting poultry manure is one of the most economical ways to reduce its negative impact on the environment (Augustyńska-Prejsnar et al., 2018). A summary of fertilizing properties of the composts produced from poultry manure is presented in Table 18.

Tab.18. Properties of composts derived from poultry manure.

No.	Parameters	MC	OM	pH	C	N	C/N	References
Units		%		-	%		-	
1	Poultry manure+ agricultural waste	54-56	35-37	8.0	17.2-18	1.2-1.3	13.6-14.4	Rizzo et al., 2015
2	Poultry manure+ wheat straw	62.2	61.8	9.21	34.3	1.03	33.3	Czekała et al., 2016
3	Poultry manure+ wheat straw+5% biochar	67.9	67.9	8.83	37.7	0.99	38.1	
4	Poultry manure+ wheat straw+10% biochar	57.6	69.3	9.29	38.5	0.80	48.1	
5	Poultry manure+poultry litter+sawdust	60.4	45.7	8.2	22.9	0.9	24.8	Young et al., 2016
6	Poultry manure+rice straw	65.3	-	9.0	28.2	2.5	11.3	Zainudin et al., 2020
7	Poultry manure+rice straw+20% biochar	36.9	-	11.0	34.4	2.4	14.9	
8	Poultry manure+ wheat straw+5% biochar	49.3	88.7	8.29	49.3	2.65	18.6	Janczak et al., 2017
9	Poultry manure+ wheat straw+10% biochar	50.2	90.1	8.04	50.1	2.45	20.4	
10	Poultry manure+ wheat straw	53.8	86.2	7.90	47.9	2.89	16.6	
11	Poultry manure+algal sludge+rice straw	28.36-39.36	53.61-55.92	6.94-8.02	-	-	-	Zhang et al., 2021
12	Poultry manure+exhausted olive cake+sesame shells	38.73	65.12	7.75	59.17	1.4	23.13	Sellami et al., 2008
13	Poultry manure+wheat straw+grass clippings+poplar bark+woodchips+grass hay	43.21	37-65	8.3-8.7	15.9-22.23	-	10.4-18.5	Vandecasteele et al., 2013

Poultry manure derived composts demonstrate various properties and can bring several advantages as reported in the literature. For example, Liu et al., (2019) investigated the effect of poultry manure compost on cadmium immobilization and toxicity in wheat crops. The application of compost provided the 50% reduction in cadmium uptake by wheat plant cells and improved wheat growth. The positive effect on the reduction of cadmium immobilization by wheat was assigned to the lowering of pH and the high dose of organic matter from the compost. Composting poultry manure also carries the potential for heavy metal-resistant microbes in the obtained composts. Zhou et al., (2021) conducted a study using poultry manure compost and biochar. Biochar had a beneficial effect on reducing the number of heavy metal-resistant bacteria. Doses of 6% of biochar had a visible effect on poultry manure compost. Biochar also reduces the mobility of microorganisms such as *Proteobacteria, Actinobacteria*, and *Bacteroidetes* resistant to heavy metals. Ravindran et al. (2022) co-composted poultry manure with sawdust, food waste and biochar to produce soil enhancers. The combination of compost mixtures, especially the addition of biochar, resulted in reduced ammonia emissions from composting and retention of nitrogen compounds in the compost. The authors concluded that the obtained compost had the fertilizing potential. Adding bulking agents to poultry manure, has an impact on the physicochemical properties of the obtained compost. Rizzo et al., (2013) prepared the compost from poultry manure and agricultural residues. The addition of bulking agents to poultry manure for composting in the form of corn residues, sawdust and wood chips had a beneficial effect on the bulk density of the compost, lowered the pH and regulated the C/N ratio. The obtained compost was found to be microbiologically safe and can be used for fertilizer purposes. Ojo et al., (2018) prepared compost from poultry manure and cassava peels. They observed that microbial biomass was correlated strictly with the production of carbon dioxide and humic acids.

Poultry manure compost can be a universal product that can be used as a soil enhancer and growing media. Depending on the requirements of the soil and the plants, the composition of the compost can be partly determined by adding bulking agents to the composting process that influence the structure of the compost mixture and the nutrient content.

2.7. Dried poultry manure

Poultry manure can be dried in dryers, ovens and in the air, using sunlight and wind. However, drying under controlled conditions of the dryer/oven has more advantages, because higher drying temperatures can be achieved. This results in a more effective and faster reduction of pathogens from the poultry manure (Ghaly et al., 2013). The properties of the obtained dried poultry manure are presented in table 19.

Tab.19. Properties of dried poultry manure.

Parameters		N	P	K	C	C/N	pH	References
No.	Units	%				-		
1	Poultry manure	3.5	3.5	1.7	+*	+	+	OZPZD, 2021
2	Poultry manure	7.5	+	+	+	+	+	Purnomo et al., 2017
3	Poultry manure (drying temperature 40°C)	4.48-4.92	2.45-2.46	1.9-1.91	+	+	6.4-6.6	Ghaly et al., 2013
4	Poultry manure (drying temperature 50°C)	4.23-4.45	2.45-2.46	1.89-1.9	+	+	6.7	
5	Poultry manure (drying temperature 60°C)	3.92-4.16	2.44-2.46	1.89-1.9	+	+	6.5-6.6	
6	Poultry manure	10.9	5.9	7.2	+	+	+	Zdanowicz and Chojnacki, 2017

+* is present, but the exact content has not been specified.

As part of the drying process, the pH of the poultry manure decreases, which also reduces the ammonia released (Gislason et al., 2003; Ghaly et al., 2013). Ghaly et al., (2012 and 2013) also confirmed that the odor emission from poultry manure was reduced by 65-70% during drying at 40-60°C. Tagoe et al., (2008) studied the effects of dried manure and poultry manure biochar on soybean growth and yield. They found that the application of dried manure fertilizer increased yield by 7-30% compared to the control. However, the application of dried manure-based biochar resulted in greater leaf growth and higher yield than with dried manure only. Many scientists confirm that dried poultry manure, biochar from dried poultry manure and granulated poultry manure also demonstrates fertilizing properties due to its high nitrogen, phosphorus, and potassium content. Dried poultry manure was also characterized by a reduced number of pathogens, pH and emissions of gases such as ammonia and carbon dioxide (Dail et al., 2007; Ghaly et al., 2012; Ghaly and MacDonald, 2012; Mazeika et al., 2016; Purnomo et al., 2017; Tańczuk et al., 2019).

3. Synthesis of the state of the art

In the European Union, 60-70% of soils are degraded by improper agricultural practices. These soils have also lost their natural ecosystem and the microorganisms residing in soil (Ferreira et al., 2021). Intensive and long-term crop production reduces organic matter content which can lead to soil degradation. Chemical fertilizers also contribute to soil nitrogen over-fertilization, disrupt plant growth cycles, and degrade the natural biomass of the microorganisms. The use of excessive amounts of chemical fertilizers can also affect surface waters, by leaching from the soil of chemical fertilizers (Ferreira et al., 2021).

Organic soil enhancers can be alternatives to chemical fertilizers. Organic soil enhancers can be prepared from food industry waste materials, agricultural residues, plant biomass and animal manure (Goss et al., 2013; Tenthacrefarm, 2022). Especially in Poland poultry manure is produced in significant quantities (more than 4 mln Mg per year). Poultry manure can be processed by composting, pyrolysis, drying, palletization and anaerobic digestion. It is possible to produce compost, biochar, dried manure, pellets, and solid state digestate (Tańczuk et al., 2019). The application of organic soil enhancers obtained from poultry manure and agricultural residues demonstrate several benefits. The application of soil enhancers influences the chemical properties of soil, e.g., increases the content of organic matter, regulates pH and C/N (Ghaly et al., 2012; Mazeika et al., 2016; Purnomo et al., 2017; Janczak et al., 2017; Rizzo et al., 2022). It affects the biological properties of the soil, i.e., increases the content of microorganisms in the soil (Das et al., 2008; Ghaly et al., 2012; Wass et al., 2020). Soil enhancer improves the physical properties of soil, i.e., increase water retention, change the soil structure (Loyon et al., 2018; Awasthi et al., 2021). Also, soil enhancers have positive effects on heavy metals and organic pollutants immobilization (Meier et al., 2017; Li et al., 2018; Sobik-Szołtysek et al., 2021; Chen et al., 2022).

Soil enhancers based on poultry manure have several applications, depending on the form in which were produced. Poultry manure derived compost is a product that has a reduced number of pathogens and unpleasant odors. It is ready to be used as soil enhancers which has a positive effect on plant growth and yield (Martínez-Blanco et al. 2013; Cesaro et al. 2015; Alsanius et al. 2016; Oliveira et al. 2017; Hu et al, 2017, Ansari et al., 2019; Lori et al., 2022).

Poultry manure derived biochar obtained by pyrolysis, has the properties of sorption, which can be used in soil bioremediation (Sobik-Szołtysek et al., 2021; Chen et al., 2022) and as a substrate in processes, i.e., composting to reduce gas emissions (Li et al., 2018; Awasthi et al., 2020, 2021). The lower the pyrolysis temperature, the more nutrients will remain in the produced biochar (Słodeczek and Głodek-Bucek, 2017).

Drying poultry manure is beneficial due to the reduction of gases, pathogens and water content, and the decrease in costs associated with transportation and storage. Dried poultry manure can be pelletized, granulated, and used as a fertilizer, or as a fuel for combustion (Myszograj et al., 2012; Wieremiej, 2017; Augustyńska-Prejsnar et al., 2018).

Over the years, the interest in work on the management of poultry manure has significantly increased. The first article on poultry manure was published in 1926 and focused on nitrogen emissions during poultry manure drying (Buckner et al., 1926). Figure 3 presents the interest in the topic about poultry manure over the last 40 years 1980-2021 expressed in the number of publications. It is worth emphasizing that between the years of 1926-1980 the number of the articles per year did not exceed 10.

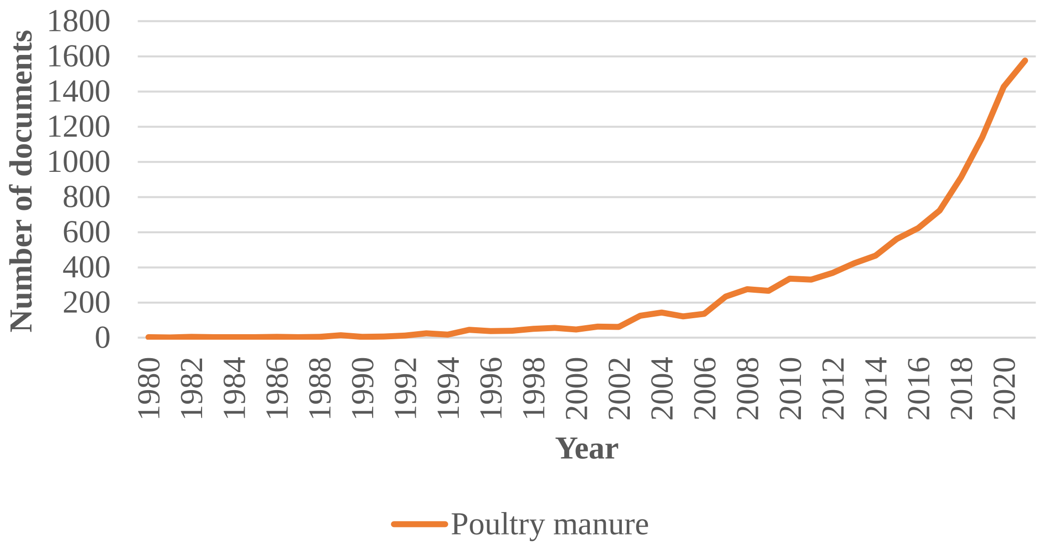

Fig.3. The number of documents about poultry manure from the period of 1980-2021 from the database Scopus (Anonymous-Scopus, 2022).

These documents included research and review article, book chapters, books, and conference papers. The total number of the documents between 1980-2021 about poultry manure from database Scopus is 9,108. Since 2000, more and more researchers have focused on the topic about poultry manure and poultry litter. Figure 4 presents the interest in poultry manure processing in terms of composting, pyrolysis and drying.

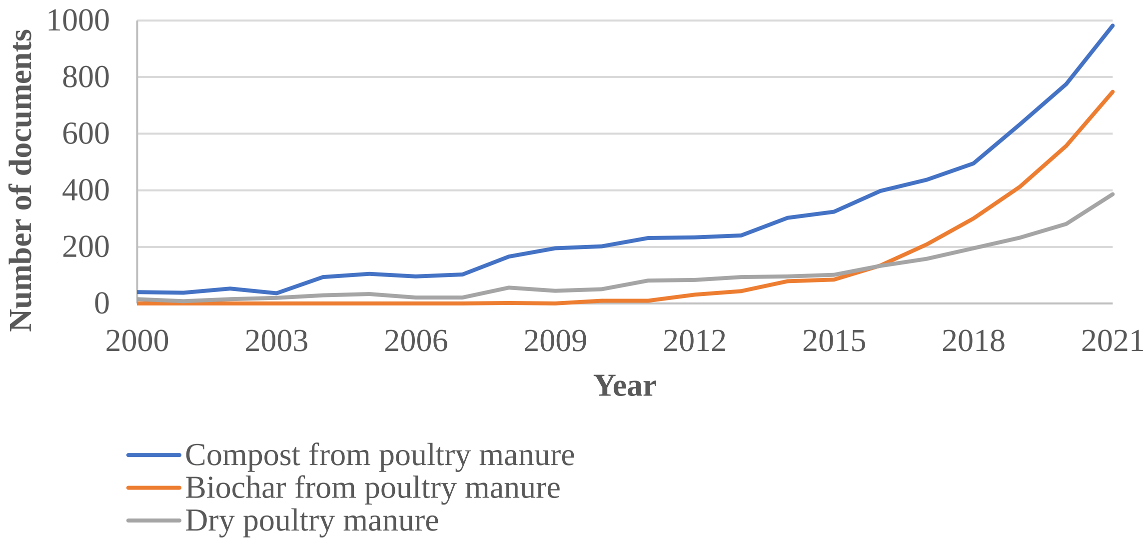

Fig.4. The number of documents about compost, biochar and dried poultry manure from the period of 2000-2021 from the database Scopus (Anonymous-Scopus, 2022).

The total number of the documents between 2000-2021 from database Scopus about compost from poultry manure is 6,976, 3,170 for biochar from poultry manure and for dried poultry manure is 2,480 documents. These documents included research and review articles, books chapters, books, and conference papers. The key words which were used to perform this analysis were as follows: compost from poultry manure, biochar from poultry manure, dried poultry manure. The knowledge about biochar is considered as the youngest field in which the articles are published. The first articles began to appear at the turn of 2007-2009.

However, the potential of poultry derived soil enhancers has not been fully investigated. Through the review of the literature, the following gaps in the state of the art have been identified:

1. The cycle of nitrogen, carbon, and phosphorus during the composting process of poultry manure is not fully understood. It is unknown exactly how much nitrogen, phosphorus, and carbon put into the composting process from poultry manure is released in the form of gaseous emissions, condensate, and leachate.

2. The literature has not provided sufficient data and examples on the water and mass balance of the poultry manure-based compost mixture.

3. The effect of poultry manure products (compost, dried poultry manure and biochar) on plant growth.

4. The effect of biochar from poultry manure produced at low pyrolysis temperature on soil properties and plant growth and yield has not been fully explained. From the performed literature review, it is noticeable that there is a higher interest in the field of soil bioremediation with biochar and less research in terms of investigating the effects on plant growth.

5. Comparison of the fertilization potential of poultry manure products (compost, dried poultry manure and biochar.) The nitrogen, phosphorus and carbon content can be different in the composition of plants that were fertilized with poultry manure products (compost, biochar, dried poultry manure) compared to plants that grew in soil without fertilizer additives.

The market's interest in organic fertilizers based on soil enhancers will be significantly influenced by the Fertilizing Product Directive, which came into force on July 16, 2022. It has expanded the possibilities for the production and sale of fertilizing products not only in the domestic market, but also throughout the European Union. It is expected that in the future this regulation will influence the development of sustainable agriculture and the recycling of waste and organic residues from agriculture and industry that can be used as fertilizing products.

III. Goals and objectives

The overall goal of this work was to investigate the potentials of poultry manure as a source to produce organic soil enhancers such as dried poultry manure, poultry manure derived biochar and poultry manure derived compost and to determine their physicochemical properties and effects on soil properties and growth of cherry tomato.

The objectives included:

1. Assessment of the potential of poultry manure derived biochar produced at different pyrolysis temperatures (475, 575, 675 and 775°C) to be used as a soil enhancer.
2. Comparison of the investigated soil enhancers (i.e., dried poultry manure, poultry manure derived biochar and poultry manure derived compost) and their effects on soil properties and plant growth.
3. Analysis of the C, N, P cycles during laboratory composting of poultry manure and wheat straw used as a bulking agent.

The following hypotheses were formulated:

1. Soil enhancers produced from poultry manure can be safely applied as soil enhancers.
2. Poultry manure derived biochar can contribute to the improvement of soil properties and plant growth.
3. Low pyrolysis temperature affects the fertilizing properties of poultry manure derived biochar.

The scope of the research work included (as presented in Figure 5):

1. Analysis of the current state of the art through literature review.
2. Physicochemical and microbiological analysis of poultry manure sampled from the cage breeding system.
3. Conversion of poultry manure into soil enhancers through:
   - composting of poultry manure in laboratory composting reactors,

- drying of poultry manure,
- pyrolyzing of poultry manure in laboratory pyrolyzing furnace,

4. The analysis of C, N and P cycles during laboratory composting of poultry manure.

5. Physicochemical analysis of the obtained soil enhancers (dried poultry manure, derived biochar, poultry manure derived compost).

6. Preparation of the growing media with the investigated soil enhancers.

7. Determination of the effects of the investigates soil enhancers on soil properties.

8. Determination of the effects of the growing media on the cherry tomato growth in the plant growth experiment.

9. Physicochemical analysis of plants and growing media after completion of plant growth experiment.

The research work was performed within the Joint PhD Program in the frame of Nutri2Cycle project (2018-2023). The timeframe with specific tasks is presents in Figure 5. The presented doctoral dissertation was carried out as part of the joint PhD program between Częstochowa University of Technology (Poland) and the University of Gent (Belgium). The research part on a) composting, b) drying, and c) pyrolysis of poultry manure was carried out at the Częstochowa University of Technology (CUT) whereas the plant growth experiment was carried out at the University of Gent (UG).

				Year	2017				2018				2019				2020				2021				2022			
				Month (period - quarter)	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**	**3**	**6**	**9**	**12**
START	**Location**	**No.**	**Task**																									
	CUT	1	Start of the doctoral studies at CUT on October 1^{st}, 2017.																									
	CUT	2	Literature review and field work.																									
	CUT	3	Physicochemical and microbiological analysis poultry manure sampled from the cage breeding system.																									
	CUT	4	Conversion of poultry manure into soil enhancers:	Composting of poultry manure in the laboratory composting reactors.																								
	CUT			The analysis of C, N and P cycles during laboratory composting of poultry manure.																								
	CUT			Drying of poultry manure.																								
	CUT			Pyrolyzing of poultry manure in the laboratory pyrolysis furnace.																								
	CUT and UG	5	Physicochemical analysis of the obtained soil enhancers (dried poultry manure, derived biochar, poultry manure derived compost).																									
	UG	6	Determination of the effects of the investigates soil enhancers on soil properties.																									
	UG	7	Determination of the effects of the growing media on the cherry tomato growth in the plant growth experiment.																									
	UG and CUT	8	Physicochemical analysis of plants and growing media after completion of plant growth experiment.																									
	CUT	9	Conlusions of the PhD research work.																									
END	CUT	10	Defense of doctoral thesis.																									

Fig.5. The timeframe with specific tasks of the PhD research work.

IV. Experimental

1. Materials

Poultry manure was sampled from a poultry farm typical for a medium-sized Polish poultry farm of 30,000-40,000 laying hens (cage breeding system) located in Cieszyn (Poland). Poultry manure was stored for a couple of days in the refrigerator (at 4° C) prior to composting. The poultry manure was removed from the refrigerator and left in the room temperature to thaw.

1.1. Poultry manure

The fresh poultry manure (Figure 6) demonstrated a dense and plastic structure with high moisture content. The investigated poultry manure contained primarily poultry droppings, bird feathers, and a small amount of egg shells. The structure of poultry manure was typical for this type of poultry farm and the cage breeding system.

Fig.6. Fresh poultry manure.

Fresh poultry manure was promptly analyzed for physicochemical properties and the obtained the results are presented in Table 20. Sampled poultry manure were also subjected to the microbiological analysis.

Tab.20. Selected characteristics of fresh poultry manure.

Parameters	**pH**	**N**	**C_{org}**	**P_2O_5**	**C/N**	**MC**	**OM**
Units	-	%	%	mg/kg	-	%	%
Poultry manure	7.51±0.19	7.91±0.01	42.32±0.02	74.70±0.17	5	78.79±0.41	74.43±0.27

Poultry manure was characterized by high concentration of nitrogen of about 8% of dry weight, phosphorus of 75 mg/kg of dry weight, and water content of about 80%. In the study by Singh et al., (2018), the nitrogen content was 5.52% of dry weight, while the C/N ratio was 3.83. The research conducted by Williams et al., (2013) indicated that phosphorus content can vary between 8-34 mg/kg of dry weight, depending on type of poultry manure and bulking agents which were used for composting. If the poultry manure is mixed with the litter, the phosphorus content is higher than in poultry manure without litter. In another study conducted by Ashworth et al., (2020), the water content was of about 75%. This difference was not significant between laying hens and broilers.

The content of selected heavy metals in the investigated fresh poultry manure was also analyzed. Lead content was <2.00 mg/kg of dry weight, cadmium 0.395 mg/kg of dry weight, chromium 11.5 mg/kg of dry weight a nickel 13.4 mg/kg of dry weight. In the work of Ravindran et al., (2017) used poultry manure from 10 different poultry farms and performed the analysis for heavy metals. Lead and cadmium were not detected, chromium and nickel were not detected in 4 samples, but in 6 samples the maximum value that tested for chromium was 38 mg/kg of dry weight and for nickel 25.7 mg/kg of dry weight.

Poultry manure was tested for the presence and number of live eggs of intestinal parasites (*Ascaris* sp., *Trichuris* sp., *Toxocara* sp.) (the laboratory of JARS in Mysłowice (Poland)). These tests were conducted in accordance with the method referred to as (Ae) PB-102/LM ed. 3 dated July 25, 2016. Microbiological analysis showed no evidence of live eggs of intestinal parasites (*Ascaris* sp., *Trichuris* sp., *Toxocara* sp.).

The wet bulk density for raw poultry manure was about 910 kg/m^3 and the air-filled porosity was 20%. For poultry manure typical values of wet bulk density is between 800-1050 kg/m^3 and the air-filled porosity in poultry manure is low, because of the wet, compacted structure of this substrate (Janczak et al., 2017).

1.2. Bulking agents

For composting poultry manure, wheat straw was selected and used as a bulking agent (Figure 7). Wheat straw is one of the most common bulking agents. The straw was harvested from the farm located near the Częstochowa, Poland.

Fig.7. Wheat straw.

The wheat straw was cut into 1-2 cm sections so that it can be easily mixed with poultry manure. Wheat straw also was analyzed for physicochemical properties which are presents in Table 21.

Tab.21. Selected characteristics of the wheat straw.

Parameters	**pH**	**N**	**C_{org}**	**P_2O_5**	**C/N**	**MC**	**OM**
Units	-	%	%	mg/kg	-	%	%
Wheat straw	6.97±0.21	0.45±0.02	36.84±0.03	2.50±0.23	82	7.94±0.45	98.47±0.24

The dry bulk density of the straw was 120 kg/m^3 and the air-filled porosity was 54%. According to the literature, the bulk density of wheat straw ranges from 97.52 to 177.23 kg/m^3, and the air-filled porosity from 46.39 to 84.24%. These parameters mainly depend on the place where the straw was harvested, climatic conditions and soil type (Zhang et al., 2014).

The wheat straw had a high C/N ratio of 82. The literature reports many studies where wheat straw was analyzed. For examples, the wheat straw used for composting of organic residues showed C/N ratio of 69:1 and moisture content were 14% (Malińska et al., 2008). Rajput et al., (2018) analyzed wheat straw in terms of changes in physicochemical properties in relation to the initial temperature. The untreated straw reached pH 5.9 while at higher temperatures, such as 180°C, the pH dropped to 4.8. Petric et al., (2012) analyzed poultry manure and wheat straw used in the composting process. The wheat straw contained 88% organic matter, pH 7.18, C/N 88, and water content 10%.

1.3. Soil

The soil used for the plant growing experiment was sampled from a plot of land that had never been treated with animal manure, located near Ghent, Belgium. The soil (Figure 8) was characterized by a loamy-sandy texture, prone to high water accumulation and clumping into larger aggregates. It also contained numerous stones. It was a typical soil that is prevalent in Belgium (SOERW, 2017).

Fig.8. Soil used for the plant growth experiment.

The soil was left for 2 weeks in the greenhouse at 20-25°C. After drying, the soil was sieved and used for the plant growth experiment. The physical and chemical properties of the soil are presents in Table 22.

Tab.22. Selected characteristics of the soil for the plant growth experiment.

Parameters	pH	N	C_{org}	C/N	MC	OM	Cr
Units	-	%		-	%		mg/kg
Soil	6.99±0.24	0.45±0.02	0.8±0.13	10	1.54±0.25	2.56±0.64	8.21±0.33

The content of heavy metals such as Pb, Cd and Ni was not detected. A study on Belgian soils was also conducted by Dassonville et. al., (2008) using 36 soil samples from different cities in Belgium for the analysis. The content of N was 0.69-3.03%, C ranging from 0.4-2.4%, C/N ratio ranging from 3.7 to 19.3: 1, and P 0.7-0.9%.

1.4. Composting mixtures

The composting mixtures were produced in the proportion of 10 kg of fresh poultry manure and 2 kg of wheat straw. Table 23 presents the proportion of substrates on a dry and wet basis.

Tab.23. Proportions of composting mixture.

	Ratio of poultry manure to wheat straw
Wet weight	1:0.06
Dry weight	1:0.26

A total of 12 kg of the composting mixture was prepared. The experiment was performed in two replications (referred to as Composting reactor No. 1 and Composting reactor No. 2 and presented individually).

1.5. Growing media

The following growing media were prepared and used for the experiment: soil (S), compost from the composting reactor No. 1 (C1), compost from the composting reactor No. 2 (C2), dried poultry manure (DPM), poultry manure derived biochar (B). Table 24 presents the description of the investigated growing media.

Tab.24. Description of growing media.

Name	Type of growing media	Composition of growing media	Ratio (Dry matter)
A	S (control)	100% soil	1
B	S + C1	3% compost from composting reactor No. 1 was added to the soil	1:0.03
C	S + C2	3% compost from composting reactor No. 2 was added to the soil	1:0.03
D	S + DPM	0.5% dried poultry manure was added to the soil	1:0.005
E	S + C1 + DPM	3% compost from composting reactor No. 1 and 0.5% dried poultry manure was added to the soil	1:0.03:0.005
F	S + C2 + DPM	3% compost from composting reactor No. 2 and 0.5% dried poultry manure was added to the soil	1:0.03:0.005
G	S + B	0.5% of biochar was added to the soil	1:0.005
H	S + B + C1	0.5% biochar and 3% compost from composting reactor No. 1 was added to the soil	1:0.005:0.03
I	S + B + C2	0.5% biochar and 3% compost composting reactor No. 2 was added to the soil	1:0.005:0.03

Due to its high nitrogen content, fresh poultry manure, as a fertilizer, is subject to high emissions, such as ammonia. High emissions of ammonia can have a negative effect on the proper function of microorganisms and plant growth. Plants exposed to prolonged ammonium stress do not reach ion balance and unfavorably pH homeostasis. Because of these factors, the plant does not develop properly, has lower biomass and less developed roots (Marino et al., 2019). For example, the application of a selected treatment to poultry manure can have the influence on physicochemical properties, e.g., reduction of ammonia during the composting process (Janczak et al., 2017; Dróżdż et al., 2020).

Hen et al., (2010) applied poultry manure compost at 0%, 2%, 4%, and 8% dose. In terms of plant biomass yield and plant height, the 2% and 4 % doses were effective, while the 8% dose did not provide such significant results. Also, Liu et al., (2009) applied poultry manure compost at doses ranging from 0.6% to 2.5%. These doses had positive effects on plant growth and reduced the accumulation and toxic effects of Cd in the soil. Das and Maiti (2009) applied poultry manure at 1.25%, 2.5% and 5.0% doeses, it was noted that poultry manure at 1.25% and 2.5% doses mixed with soil resulted in significantly higher dry biomass than the 5% dose. Meiera et al., (2015) used 0.5% and 10% biochar from poultry manure, and they reported beneficial effects on plant biomass. There was a three-fold increase in plant biomass in the sample with 0.5% biochar compared to the control. Masud et al., (2020) studied the effect of poultry litter and poultry manure biochar at doses of 0.5%, 1% and 1.5% on maize growth. The growth of plant biomass was more beneficial with the addition of biochar, especially at the dose of 1 and 1.5%. The doses of the investigated soil enhancers selected for the experiment constituted the average value adopted from the performed literature review.

2. Methods

2.1. Physicochemical analyses

The following analyses were performed to determine the physicochemical properties of the investigated materials: moisture content, organic matter, pH, EC, Kjeldahl nitrogen, available phosphorus, organic carbon, total organic carbon, ammoniacal nitrogen and heavy metals.

Moisture content (MC) was determined based on the legal norm PN-75/C-04616.01 by the laboratory drier (Dryer 30L PRO) and calculated from the following formula (1):

$$MC\ [\%] = \frac{(m1-m2)}{(m1-m)} * 100 \quad (1)$$

where:

m – the weight of the container, g

m_1 – the weight of the container with the material before drying, g

m_2 – the weight of the container with the material after drying at 105°C, g

Organic matter (OM) was determined, based on the legal norm PN-75/C-04616.01, by laboratory oven Estherm, and calculated from the following formula (2):

$$OM\ [\%] = \frac{(m2-m3)}{(m2-m)} * 100 \quad (2)$$

where:

m – the weight of the container, g

m_1 – the weight of the container with the material before drying, g

m_2 – the weight of the container with the material after drying at 105°C, g

m_3 – the weight of the container with the material after combustion at 550°C, g

pH was determined, based on the legal norm PN-EN 15933:2013-02E, by laboratory pH-meter, Elmetron CPC-505.

Electrical conductivity (EC) was determined, based on the legal norm PN-EN 27888:1999, by Elmetron CPC-505.

Kjeldahl nitrogen was determined, based on the legal norm PN-Z-15011-3. The name of the analyzer that was used for testing is steam stiller model K-350, and calculated from the following formula (3):

$$V\ [\%] = \frac{1.4(VHCl-VNaOH)*100}{500} \quad (3)$$

where:

1.4 – the number of milligrams of nitrogen that corresponds to 1 cm^3 of 0.1M HCl solution

500 – sample weight, mg

V_{HCl} – volume of 0.1M HCl solution used, ml

V_{NaOH} – the volume of 0.1M NaOH solution used, ml

Available phosphorus (P_2O_5) was determined, based on the methodology of laboratory analysis of soils and plants according to "Methodology of laboratory analysis of soils and plants" written by Karczewska A. and Kabała C., (2008). The name of the analyzer was Uv-vis spectrophotometer Hach Lange DR 5000.

Ammoniacal nitrogen was determined, based on the legal norm PN-76/C-04576/01 and calculated from the following formula (4):

$$V\ [mg/dm^3] = \frac{1.4(VHCl - VNaOH) * 1000}{Vpr} \quad (4)$$

where:

1.4 – the number of milligrams of nitrogen that corresponds to 1 cm3 of 0.1M HCl solution

V_{pr} – sample volume, ml

V_{HCl} – volume of 0.1M HCl solution used, ml

V_{NaOH} – the volume of 0.1M NaOH solution used, ml

Organic carbon (C_{org}) was determined, based on the legal norm PN-EN 15936:2013-02E, and calculated from the following formula (5):

$$C_{org}\ [\%] = \frac{OM}{1.8} \quad (5)$$

where:

OM – content of organic matter, %

Total Organic Carbon (TOC) was determined according to Jarvie et al., (1991), by the analyzer of Carbon Analyzer Multi N/C 2100, Analytikjena.

The concentrations of the following elements, i.e.: P, S, Ca, Mg, Na, K, Al, Cr, Cu, Fe, Mn, Pb, Zn, Cd, Co, Ni were determined with Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The analyzes were performed according to the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization from 2007. These analyzes were performed by analyzer ICP OES Vista-MPX.

2.2. Production of soil enhancers

Poultry manure was converted through a) composting into compost, b) pyrolysis into biochar, and c) drying into dried poultry manure. The obtained soil enhancers were analyzed for C_{org}, N, P_2O_5, MC, SO, pH and EC content, nutrient (Ca, Mg, Na, K, Al, Fe, Mn, Zn, Co), and heavy metal content (Cr, Cu, Pb, Cd, Ni).

Microbiological analyzes were also performed in the laboratory of JARS in Mysłowice (Poland) where raw poultry manure and composts from poultry manure were tested for the presence and number of live eggs of intestinal parasites (*Ascaris* sp., *Trichuris* sp., *Toxocara* sp.). The tests were conducted in accordance with (Ae) PB-102/LM ed. 3 dated July 25, 2016.

The microbial analysis for *Escherichia coli* (legal standard Pr PN-Z-19000-2) and *Salmonella* (legal standard PN-Z-19000-1) was conducted at Czestochowa University of Technology.

2.2.1. Composting

The prepared composting mixtures were composted in the laboratory composting reactors for 40 days and after that, the composting mixtures was left to mature for 5 months. The aeration rate during composting was at the level of 35-40 dm^3/h. The composting mixtures after two weeks were removed from the composting reactors for mixing and sampling. Czekała et al. (2016) also conducted a mixing in half of the composting process for improving the aeration and taking samples for the analysis. The temperature in the composting reactors was measured daily. During composting the composting mixtures were sampled at the beginning, in the middle, at the end of the composting and after 5 months of maturation. Figure 9 presents the matured, dried, and ground poultry manure derived compost.

Fig.9. Poultry manure derived compost.

2.2.2. Pyrolysis

Poultry manure was thermally converted in the laboratory pyrolysis furnace. The laboratory setup for pyrolysis is presented in Figure 10.

Fig.10. Laboratory pyrolysis furnace for biochar production.

The pyrolysis was carried out with an inflow of 5 L/min of nitrogen supplied to furnace. The selected heating temperatures were following: 475, 575, 675 and 775°C. Heating of the poultry manure samples took 120 minutes and the retention time was 60 minutes. The study was performed according to the process parameters, described by Sobik-Szołtysek et al., (2021). Figure 11 presents the final product, i.e., ground poultry manure derived biochar.

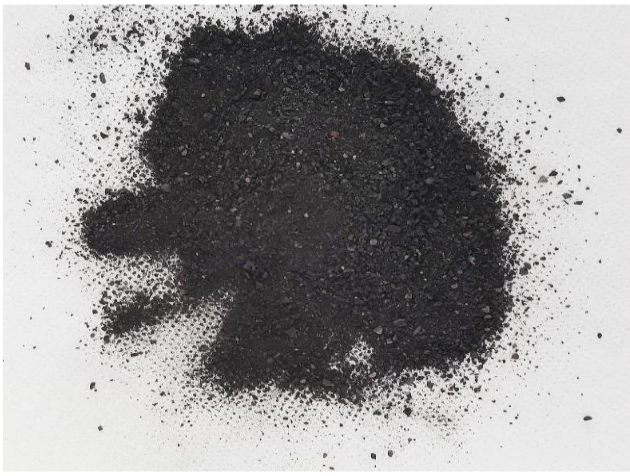

Fig.11. Poultry manure derived biochar.

2.2.3. Drying

Fresh poultry manure was placed on a plate and set in a laboratory dryer (model 30L PRO) where a drying temperature of 105°C was maintained (Figure 12).

Fig.12. Laboratory dryer (model 30L PRO).

The poultry manure remained in the laboratory dryer until it became constant in weight. The poultry manure was dried at 105°C to maximize water removal. First part of the dried poultry manure was used to produce biochar, while second part was ground and used for further experiments as dried poultry manure. Figure 13 presents dried poultry manure before grinding.

The dried poultry manure was ground in a knife grinder (PULVERISETTE 11) to fractions of less than 3 mm.

Fig.13. Dried poultry manure.

2.3. Preparation of the growing media

Each growing medium (A-I) was prepared in five replicates as presented in Table 26. About 1 kg of each growing medium was transferred into a pot to run the plant growth experiment.

Tab.26. Selected growing media for the plant growth experiment.

Name of the growing media	Characteristic	Replication No. 1	Replication No. 2	Replication No. 3	Replication No. 4	Replication No. 5
A	*S (control)					
B	S + C1					
C	S + C2					
D	S + DPM					
E	S + C1 + DPM					
F	S + C2 + DPM					
G	S + B					
H	S + B + C1					
I	S + B + C2					

* Soil (S); the compost from the composting reactor No. 1 (C1); the compost from the composting reactor No. 2 (C2); dried poultry manure (DPM); poultry manure derived biochar (B).

2.4. Plant growing experiment

Cherry tomatoes were selected for the plant growing experiment. Seeds were first sown into a growth tray (Figure 14) that had been previously filled with moist medium (coconut fiber/peat mixture) (Figure 15). The growing was carried out in the phytotron chamber at temperature of 23-26°C. The seeds started to germinate after 4 days, and after 2 weeks they were prepared for repotting into pots with growing media (they grew to a height of 3.5-4 cm). After repotting, the plants were placed in the phytotron chamber.

Fig.14. The growth medium of Bio RHP 10 L.

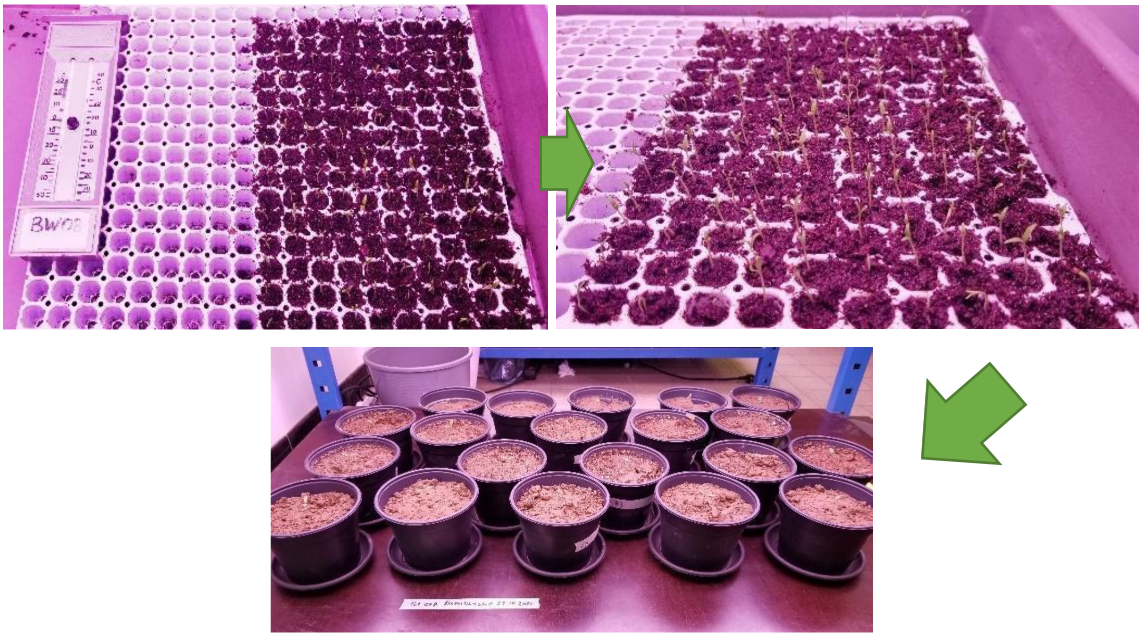

Fig.15. Growth phases of cherry tomatoes.

3. Experimental setups

Two experimental setups were used to conduct the laboratory experiments, i.e., the laboratory composting setup (located in the laboratory at Częstochowa University of Technology) and the plant growing system in the phytotron chamber (located in the laboratory at Ghent University).

3.1. Laboratory composting setup

The laboratory composting setup consisted of the insulated laboratory composting reactors with 60 L volume each, the forced aeration system with the oxygen flow regulators, the temperature probe, the containers for collecting leachate and condensate which also served as the system for capturing gases from the outlet air, i.e., NH_3 and CO_2 (Figure 16 and 17).

Fig.16. Laboratory composting setup.

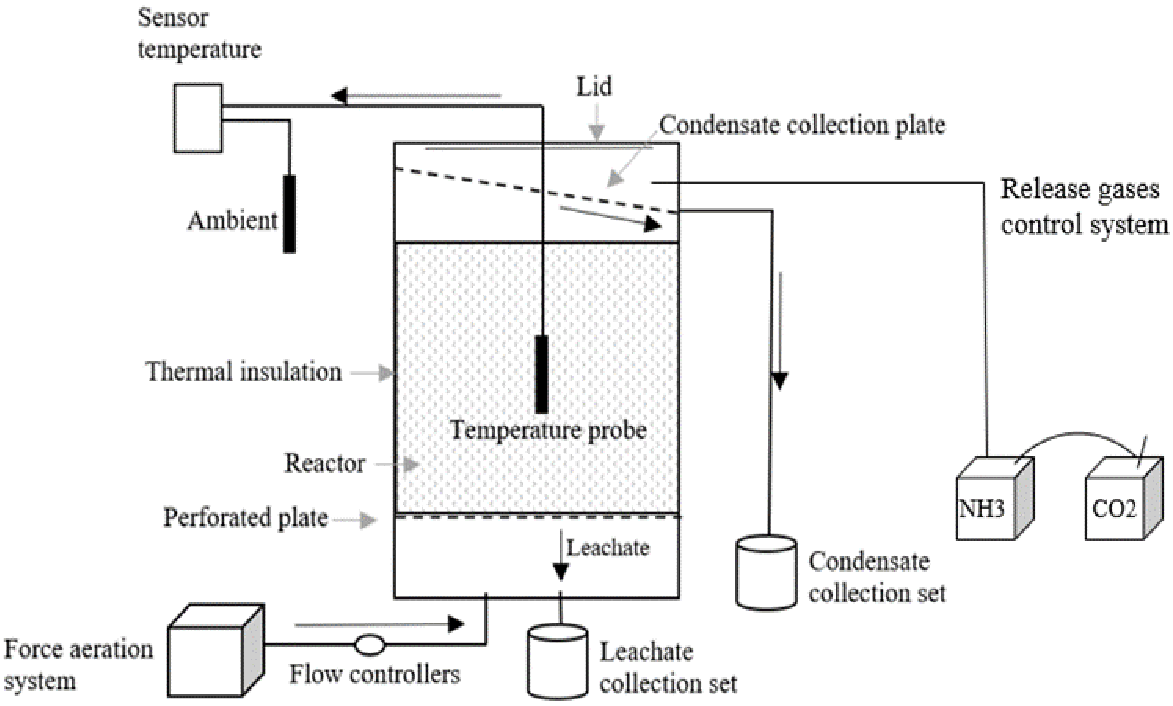

Fig.17. Schematic layout for a single composting reactor (Dróżdż et al., 2020a).

3.2. Laboratory plant growing system

The plant growth experiment was conducted in a phytotron chamber. The chamber had the controlled temperature and artificial lighting. The plants were exposed to light for 16 hours per day as recommended in the literature and to avoid the stress of insufficient light (Horticultural Password, 2004; Shi et al., 2022). The specification of the lamps was as follows: Sylvania gro-lux f36W/gro t8 bulbs of 8500K, 1200 mm long and 28 mm wide (Figure 18). Light distribution on the shelves was controlled using the Quantum Model MQ-500 meter with a separate sensor.

Fig.18. The layout of the cherry tomatoes in the phytotron chamber plants during the plant growth experiment.

V. Results and discussion

1. Properties and fertilizing potential of the obtained soil enhancers

Soil enhancers obtained through biological, chemical, and physical processes are required to comply with several requirements of the Regulation of the European Parliament and of The Council (EU) 2019/1009 of June 5, 2019. A soil enhancer is characterized with organic matter content, organic carbon content, water content, heavy metals, and microbiological test.

1.1. Poultry manure derived biochar

Poultry manure derived biochar was produced by pyrolysis at four temperatures: 475°C, 575°C, 675°C and 775°C. The biochar yield from one kilogram of poultry manure at temperatures of 475°C, 575°C, 675°C and 775°C, was 52.8%, 43.9%, 42.6% and 40.2% respectively. Similar results, regarding the decrease in the yield of biochar from poultry manure with increasing pyrolysis temperature, were reported by Bavariani et al. (2019) and Sobik-Szołtysek et al., (2021). The yield of biochar production depends mainly on the used type of pyrolysis substrate.

To analyze the properties of the obtained biochars and select one type of biochar for testing in the plant growing experiment a detailed analysis of chemical composition and physicochemical properties was performed.

The biochar that will be used for soil fertilizing should be safe for the environment. To assessing and obtaining a quality certification that conforms to safety standards, there are several organizations on the market that certify plant-based biochar (Malińska et al., 2016). These are the IBI Biochar Standards, European Biochar Certificate (EBC) and Biochar Quality Mandate (BQM). The quality requirements for biochar input into the soil include the content of heavy metals (As, Cd, Cr, Cu, Pb, Hg, Ni and Zn), polycyclic aromatic hydrocarbons (PAH-16), polychlorinated biphenyls (PCB-7), and furans and dioxins (PCDD/F), dry matter content, pH, total organic carbon (TOC), nitrogen (N) and potassium (K) total, phosphorus (as P2O5), total calcium (Ca) and magnesium (Mg) (REFERTIL Recommended Biochar Quality, 2018). According to the guidelines of REFERTIL Recommended Biochar Quality (2018), a set of physicochemical analyses of poultry manure derived biochar were performed and the obtained results were compared with the reference values for The European Biochar Certificate (EBC).

The properties of biochars obtained at selected pyrolysis temperatures were presented in table 27.

Tab.27. Comparison of selected properties of the obtained biochars with the EBC guidelines.

Parameters	Units	Biochar from 475°C	Biochar from 575°C	Biochar from 675°C	Biochar from 775°C	EBC standard
MC	%	4.44±2.87	4.08±2.92	4.41±2.33	4.00±2.50	>60
OM		39.47±2.30	33.00±2.88	37.39±3.05	24.60±3.12	-**
pH	-	12.04±0.02	13.24±0.03	12.55±0.14	13.40±0.12	6-10
N	%	3.73±0.02	3.05±0.01	3.07±0.02	3.69±0.04	-
TOC		30.76±0.02	29.89±0.01	30.56±0.03	30.29±0.02	20
C/N	-	8.18	9.8	9.95	9.87	-
Ca	mg/kg	1469.00±0.02	1466.64±0.03	1403.38±0.04	1487.14±0.02	-
K		324.80±0.04	359.00±0.05	301.98±0.05	266.72±0.06	-
Mg		100.12±0.03	112.44±0.02	100.67±0.03	93.65±0.07	-
Na		281.70±0.02	341.69±0.01	271.07±0.06	263.59±0.02	-
P		1927.61 ±0.02	1902.34±0.09	1723.31±0.08	1546.66±0.04	-
S		95.86±0.14	255.25±0.12	238.74±0.22	298.46±0.02	-
Al		35.76± 0.02	-*	14.76± 0.04	25.12± 0.03	-
Cd		0.80± 0.03	0.3± 0.02	0.3± 0.03	0.4± 0.03	1.5
Co		0.33± 0.02	-	1.60± 0.02	0.36± 0.03	-
Cr		0.12± 0.02	-	-	-	100
Cu		0.55± 0.04	0.12± 0.03	-	0.46± 0.03	200
Fe		3.88± 0.03	3.19± 0.04	4.25± 0.04	2.13± 0.03	-
Mn		-	-	-	-	-
Ni		2.43± 0.02	0.80± 0.01	-	3.97± 0.02	50
Pb		-	3.65± 0.02	-	-	120
Zn		2.25± 0.03	2.36± 0.04	1.96± 0.02	1.53± 0.04	600

-* not detected; -** no limit values for certification.

Several researchers (Chen et al., 2014; Subedi et al., 2016; Jin et al., 2017; Sobik-Szołtysek et al., 2021) have confirmed that the higher the process temperature was, the more ash was present in biochar. Consequently, the high content of ash increases the pH of the obtained biochar. Domingues et al., (2017) while studying biochar derived from the mixture of poultry manure and coffee bean shells observed that biochar at 350-450°C has a lower specific surface area and higher water absorption. Furthermore, it can absorb N-NH_4 and reduce nitrogen loss during leaching. This means that biochar from poultry manure could be also used as an additive to composting mixtures with high nitrogen content materials and the obtained composts could be applied as soil enhancers (Li et al., 2018; Chen et al., 2020). Chen et al., (2020) used the addition of biochar from poultry manure during composting of poultry manure. They found that the addition of 4 and 6% biochar reduced the release of greenhouse gases from the composter, such as methane by 19-27%, nitrous oxide by 9-55% and ammonia by 24-56%. The addition of biochar had a positive effect on the extension of the thermophilic phase and maturation of the poultry manure compost. Ronix et al., (2021), studied the effect of poultry manure biochar addition on soil properties and plant growth. The addition of 5% biochar increased organic matter content and improved soil structure. Biochar had a positive effect on cabbage growth. Mierzwa-Hersztek et al., (2016) examined the effect of poultry manure biochar toxicity on soil and soil microorganisms and tested the effect of the additive on plant biomass growth (e.g., forage grass). They found that biochar was not toxic to soil and soil microorganisms (including *Vibrio fischeri, Heterocypris incongruens*). The addition of biochar to the soil increased plant biomass by 30% compared to the addition of fresh poultry manure. Sobik-Szołtysek et al., (2021) have proven that the higher the pH of biochar, the better its ability to absorb heavy metal ions. This report is valuable for the use of biochar in soil bioremediation.

In the presented experiment, the pH ranged between 12 and 13. According to The European Biochar Certificate (EBC), (2022), the pH of biochar should range from 6-10. However, this parameter applies to biochar from plant biomass and not animal origin biomass. According to the literature, the pH for biochar obtained from animal manure is in the range of 7-13 (Qi et al., 2017; Bavariani et al., 2019; Adekiya et al., 2019; Agbede et al., 2020; Sobik-Szołtysek et al., 2021; Hossain et al., 2021). In terms of heavy metals, their content in biochar from poultry manure did not exceed the standards set by the ECB, (2022) and the Regulation of the Minister of Agriculture and Rural Development of June 18, 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization from 2007.

Based on the presented properties of the obtained biochars: the biochar obtained at 475°C was selected as a soil enhancer to be used as an additive in the growing media. This biochar was characterized by the lowest pH, higher organic matter content and micro and macro-nutrients. The selection of biochar from the lowest pyrolysis temperature (475°C) was also determined by the fact that there is limited knowledge about the effects of biochar from poultry manure obtained at the temperature 475°C on soil properties and plant growth. This problem was also noted by Hossain et al., (2021).

The interest in poultry manure derived biochar and its use as a soil enhancer has been the focus of numerous studies for less than 15 years. According to the literature, some of the first studies on the properties of biochar from animal manure occurred in 2008, and since then scientists have been trying to fill the gaps in the state of the art (Anonymous-Scopus, 2022). Therefore, addressing the challenges of obtaining biochar from a variety of temperatures and substrates, including animal manure, is currently of the major interest to researchers.

1.2. Dried poultry manure

Dried poultry manure which was obtained at the stage of preparing poultry manure for pyrolysis was also considered as a soil enhancer and was tested for fertilizing properties.

Physicochemical analysis of dried poultry manure

The selected characteristics of dried poultry manure are presented in table 28.

Tab.28. Physicochemical analysis of dried poultry manure.

Parameters	pH	C	N	C/N	P_2O_5	P	S	Mg	Na	MC	OM
Units	-	%		-	mg/kg					%	
Dried poultry manure in 105°C	7.01± 0.02	41.35± 0.01	7.92± 0.12	5.22	11.61± 0.13	78.27± 0.03	23.45± 0.02	1681.9± 0.01	1290± 0.02	4.81± 0.19	68.49± 0.22

Similar results were obtained by other researchers. For example, Kic et al., (2013) reported a significant decrease in moisture content (MC) from 80% to 10%. Drying poultry manure in 105°C caused the decrease in pH in comparison to the fresh poultry manure from 7.51 to 7.01. Ghaly et al. (2012) dried poultry manure at 60°C and observed a decrease in pH from 8.4 to 6.9 in comparison to untreated poultry manure.

Comparing the results obtained in terms of nitrogen content, with other researchers, the results were similar. Nitrogen content ranges from 4-10% in dried poultry manure (Ghaly et al., 2013; Purnomo et al., 2017; Zdanowicz and Chojnacki, 2017; OZPZD, 2021).

Heavy metal content in dried poultry manure

Dried poultry manure was also analyzed for the content of heavy metals. The obtained values were compared with the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 and Regulations (EC) No 1069/2009. The results are presented in table 29.

Tab.29. Heavy metal content in dried poultry manure compared to legal norms.

Parameters	Al	Cr	Cu	Fe	Mn	Pb	Zn	Cd	Co	Ni
Units	mg/kg									
Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 and, Regulations (EC) No 1069/2009	No data	100	600	No data	No data	140	1500	5	No data	60
Dried poultry manure in 105°C	233.23± 0.03	-*	6.74± 0.03	409.64± 0.03	108.44± 0.02	-	117.79 ±0.04	-	-	-

-* not detected.

The regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization from 2007 and Regulations (EC) No 1069/2009, the contents of heavy metals in dried poultry manure did not exceed the limits. The content of heavy metals in the poultry manure is mainly related to the food which poultry received in the farmyard and the feed the poultry received in the poultry house (Wang et al., 2013; Ravindran et al., 2017). Similar results on the content of heavy metals were obtained by Zhang et al., 2012; Wang et al., 2013; Irshad et al., 2013 and Ravindran et al., 2017. In all these studies the content of heavy metals did not exceed regulatory limits.

2. Effects of the obtained soil enhancers on soil properties

In general, soil enhancers are expected to have a positive effect on soil properties. Soil enhancers reduce bulk density in the soil and contribute to the stability of soil aggregates and soil aeration. Soil enhancers are also expected to facilitate the uptake of elements that are in the forms not available to plants, in particular phosphorus and nitrogen (Liu et al., 2014; Ansari et al., 2019).

Poultry manure has a high nitrogen content, which is necessary for plant growth. To maximize the fertilizer potential of poultry manure, it can be used to produce compost, biochar, and dried poultry manure. Soil enhancers based on poultry manure improve soil bulk density, aeration, water retention, organic matter content, microbial activity, and cation exchange capacity (Mohamed et al., 2010; Adeyyemo et al., 2019; Ansari et al., 2019). The natural free flow of water in the soil after the application of poultry manure-based soil enhancers improves soil properties (Oyonarte et al., 2002; Adeyyemo et al., 2019). The access to water and air in the soil has a beneficial effect on nutrient cycling involving microorganisms (Lowery et al., 1996). Adding poultry manure-based soil enhancers to sandy soils increases soil water retention by up to 18% (Martens and Frankenberger, 1992; Eusufzai et al., 2012). In turn, the addition of soil enhancers to clay soils reduces soil aggregate compaction and improves aeration (Adeyyemo et al., 2019).

The results obtained from the physicochemical analyzes of the investigated growing media, i.e.: soil enhancers in the form of compost, biochar and dried poultry manure mixed with soil are presented in table 30.

Tab.30. Physicochemical characteristics of the investigated growing media prior to the plant growth experiment.

Growing media	Units	A	B	C	D	E	F	G	H	I
Parameters		**S***	**S+C1**	**S+C2**	**S+DPM**	**S+C1+DPM**	**S+C2+DPM**	**S+B**	**S+C1+B**	**S+C2+B**
N	%	0.08±0.02	0.14±0.02	0.14±0.02	0.10±0.01	0.16±0.03	0.20±0.02	0.11±0.04	0.17±0.03	0.18±0.02
C		0.80±0.02	1.63±0.04	1.70±0.06	0.92±0.01	1.83±0.05	1.87±0.08	1.04±0.03	1.88±0.04	2.01±0.02
MC		1.54±2.02	5.44±0.12	4.46±1.32	4.65±1.72	4.81±2.02	5.49±2.62	3.92±2.92	3.69±3.02	3.38±2.09
OM		2.56±3.02	4.57±2.32	7.27±3.08	4.30±2.02	4.46±3.02	3.71±2.62	3.91±2.32	4.20±2.09	4.19±2.52
pH	-	6.99±0.02	7.13±0.02	7.16±0.03	7.96±0.07	7.33±0.03	7.35±0.02	8.10±0.02	7.62±0.06	7.53±0.04
C/N		10.00	11.64	12.14	9.20	11.43	9.35	9.45	11.06	11.17
P	mg/kg	131.90±0.02	247.99±0.02	236.47±0.03	211.44±0.04	305.22±0.03	256.15±0.02	210.72±0.01	292.30±0.07	381.88±0.04
S		51.78±0.04	98.46±0.02	95.16±0.02	74.73±0.03	117.45±0.07	115.30±0.05	70.07±0.03	121.08±0.04	146.93±0.04
Ca		826.56±0.02	1127.26±0.02	1341.55±0.01	855.54±0.03	1227.22±0.03	1198.53±0.05	1092.16±0.06	1275.51±0.03	1769.16±0.03
Mg		595.93±0.02	598.18±0.02	678.12±0.08	671.95±0.05	690.50±0.04	647.31±0.03	641.36±0.03	599.03±0.07	698.02±0.04
Na		3719.8±0.02	2440.34±0.04	2828.54±0.04	3484.74±0.04	2737.85±0.07	2938.96±0.03	3394.5±0.08	2359.7±0.07	2468.82±0.09
K		2396.14±0.04	2098.92±0.03	2329.64±0.02	2451.38±0.02	2367.98±0.01	2314.18±0.05	2387.12±0.05	1979.20±0.02	2281.28±0.05

* Soil (S); the compost from the composting reactor No. 1 (C1); the compost from the composting reactor No. 2 (C2); dried poultry manure (DPM); poultry manure derived biochar (B).

Mixing the soil enhancer with the soil with a pH of 6.99 increased the pH of all the growing media. The most significant increase in pH was observed for the growing medium G, i.e., the mixture of soil and biochar from poultry manure where the pH was 8.10. High pH is typical for poultry manure derived biochar, and the pH can range from 7 to even 13 (Bavariani et al., 2019; Chen et al., 2020; Sobik-Szołtysek et al., 2021).

Adding the compost from the composting reactor No. 1, the compost from the composting reactor No. 2, biochar and dried poultry manure caused the increase in the content of N, C, OM, and micro and macro elements.

The same conclusions regarding the increase in the nutrient content after the application of soil enhancers based on poultry manure in soil were noted by Dail et al., (2007), Jeffery et al., (2011), Ghaly et al., (2012), Ghaly and MacDonald, (2012), Crane-Droesch et al., (2013), Mazeika et al., (2016), Purnomo et al., (2017); Tańczuk et al., (2019), Adeyyemo et al., (2019), Ansari et al., (2019) and Jindo et al., (2020).

Lentz et al., (2012) used poultry manure derived biochar as a soil enhancer by mixing soil and producing growing medium with the 1.5-fold increase in soil Mn content, the 1.40-fold increase in C content and the 1.2-1.7-fold increase in other nutrients compared to the control (soil only). Adekiya et al., (2019) applied poultry manure and poultry manure derived biochar which also had a positive effect on soil. Especially in organic matter content which increased by 5-30%.

3. Effects of the obtained soil enhancers on the growth of cherry tomatoes

3.1. Effects of soil enhancers on plant growth

The effects of the obtained growing media after the addition of the investigated soil enhancers were determined from the analysis of growing cherry tomatoes in the 6-week pot experiment.

The experiment was documented with photos presented in table 31. The growth of cherry tomatoes was monitored for 6 weeks until blooming.

Tab.31. The growth of cherry tomatoes in the 6-week pot experiment.

Growing media	Week 1	Week 3	Week 6
A			
B			
C			
D			
E			
F			
G			
H			
I			

Plant growth was reported in all growing media. However, only 2 out of 5 plants germinated in the growing medium D. This can be due to the fact that the growing medium D was a combination of soil and dried manure which become excessively high dose of nitrogen, especially in the form of ammonia for the plants. Dried poultry manure was dried at 105°C, gas emissions were not removed from this soil enhancers as high as from compost or biochar which can result in a deficiency in plant germination (Czekała et al., 2017, Janczak et al., 2016). Ammonia emissions change the pH of the rhizosphere, thus affecting the diversity of microorganisms in the soil and their interactions with plants. Excessive ammonia emissions can inhibit plant growth (Weise et al., 2013). Also, Borkowski et al., (2014) found that too high salinity in NaCl can inhibit tomato growth. The plants also had difficulty accessing potassium ions because in an acidic medium, plant roots assimilate this element more efficiently. Also, in the growing medium D the content of Na (3485 mg/kg in dry weight) and K (2452 mg/kg in dry weight) was much higher than in other growing media. This could have also caused some limitations to the plant growth.

A demonstrable growth effect was observed for the growing media E, F, G, H, and I. The increase in plant biomass was due to the combination of compost and biochar from poultry manure which were rich in organic matter, supporting soil microbial activity and plant growth. Due to physical and thermal processes, the compost and biochar from poultry manure had a stable structure, limited gas emissions, and a high content of micro- and macro-elements. All these elements contributed to improving soil properties (Adeyyemo et al., 2019; Ansari et al., 2019; Dyśko, 2019). The beneficial effect of applying poultry manure compost is confirmed, by Abdelhamid et al., (2004) who applied 20 to 200 g of poultry manure compost per 1000 g soil. They observed that 20 g of poultry manure compost per pot was enough to see a significant increase in plant biomass (faba bean). A similar situation was observed by Revell et al. (2012) who applied 5% of poultry manure derived biochar to a sandy soil in which lettuce and peppers were planted. They observed the growth of both plants to be about 50% higher than in soil without additives. They also confirmed that the poultry manure biochar increased soil pH and phosphorus content. The biochar also had a positive effect on water retention in the sandy soil which increased from 15% to 27%.

After the growth period, the plant stalk and plant biomass were also measured in addition to visual observation. Figure 19 and 20 presents the obtained results.

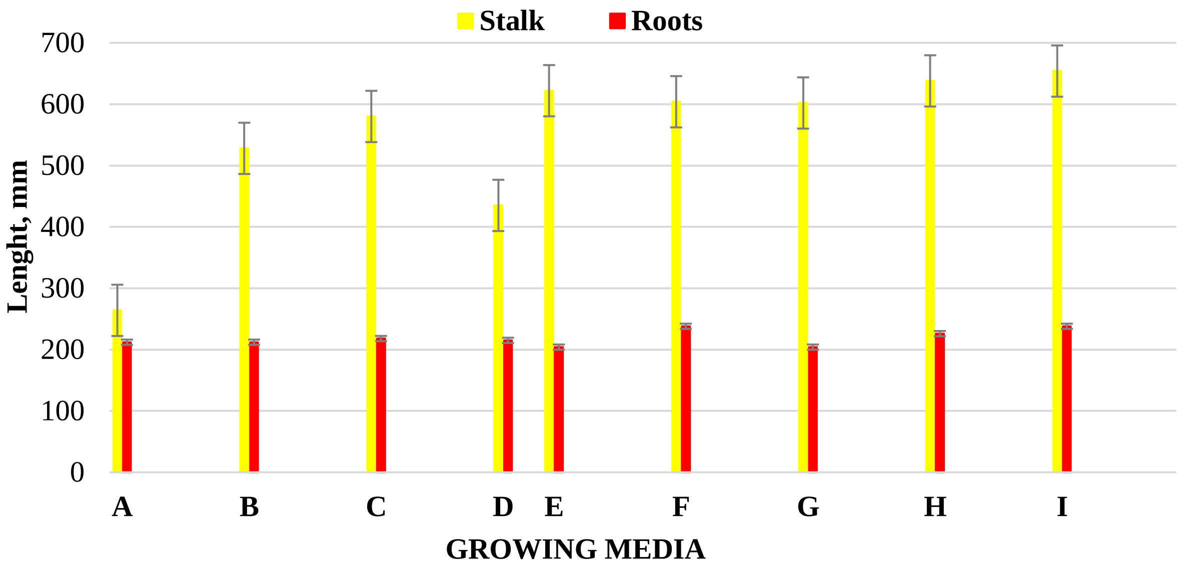

Fig.19. The comparison of the length of stalk and roots of cherry tomatoes grown on the investigated growing media.

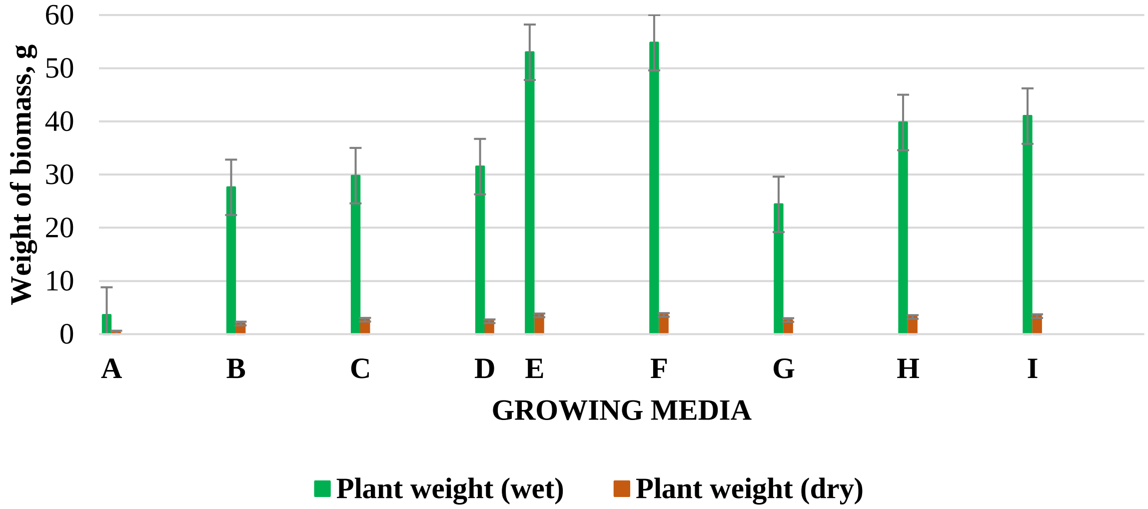

Fig.20. The mass of fresh and dried plants after 6 weeks of growth.

The growing medium F obtained the highest plant biomass. On average, the plants reached about 56 g of wet weight (3.61 g of dry weight). The growing medium F was the mixture of soil and poultry manure derived biochar. Sikder et al., (2018) observed that the addition of poultry manure biochar has a significant effect on the obtained plant biomass, compared to the application of dried poultry litter. Similar conclusions were also reached by Bhattarai et al., (2015) who applied poultry manure derived biochar in pea (*Pisum sativum L.*) growth.

The lowest plant biomass was obtained from the growing medium A with 3.6 g wet weight (0.24 g dry weight). Ojeniy et al., (2008) and Usman (2015) also noted the positive effect of poultry manure on tomato growth compared to the soil without any treatments (control). Most of the plant consists of almost 90% water, so the mass obtained after drying can be even several times lower (Liberacki et al., 2017).

The measurements of the height of cherry tomatoes showed that the growing media G, H and I, i.e., the mixture of soil, compost and biochar, allowed the plants to obtain from 602 to 654 mm in height. Similar results were obtained by Musa et al., (2020) where tomatoes obtained the height of 400-450 mm after using dried poultry manure and biochar from poultry manure, compared to the soil without additives the height of the tomatoes did not exceed 300 mm. Guo et al., (2021), also observed that tomatoes gained 16-39% increased height after applying biochar at a dose of 30 to 50 t/ha. However, the higher dose of biochar 51-70 t/ha resulted in reduced plant growth, as the proper function of soil microorganisms was affected by the excess nutrients.

3.2. Changes in the growing media after the completion of the plant growth experiment

The use of the growing media (B-I) based on poultry manure resulted in a positive effect on soil properties and a significant increase in the biomass of cherry tomatoes compared to the growing medium A. The reduction in the content of organic matter in the soil at the end of the plant experiment means that it was used by soil microorganisms and the plants themselves to absorb the necessary elements for leaf and root growth and development (Schulz et al., 2013; Musa et al., 2020). All the results obtained after the 6-week plant growth experiment were presented in table 32.

Tab.32. Physicochemical characteristics of the investigated growing media after the completion of the plant growing experiment.

Parameters	**pH**	**N**	**C**	**MC**	**OM**	**C/N**	**Ca**	**K**	**Mg**	**Na**	**P**
Units	-	%				-	mg/kg				
A	7.06±0.02	0.06±0.02	0.87±0.02	2.26±2.12	2.82±3.15	14.55	293.8±0.10	263.2±0.21	183.3±0.10	50.0±0.12	46.5±0.10
B	7.58±0.02	0.13±0.03	1.44±0.06	2.51±2.02	2.00±3.19	11.32	524.1±0.12	282.2±0.22	189.3±0.11	52.6±0.18	72.1±0.21
C	7.55±0.06	0.12±0.03	1.43±0.07	2.62±2.98	2.02±2.45	12.03	405.7±0.19	299.9±0.21	184.4±0.11	56.5±0.15	74.1±0.23
D	6.82±0.05	0.09±0.04	1.01±0.09	2.28±3.02	2.28±3.12	11.15	335.7±0.18	245.4±0.19	179.7±0.24	45.0±0.19	54.3±0.34
E	7.61±0.08	0.14±0.03	1.54±0.06	3.22±3.12	4.82±2.98	11.15	413.2±0.15	300.9±0.10	187.1±0.34	49.1±0.17	91.7±0.32
F	7.56±0.09	0.15±0.04	1.66±0.10	1.62±3.82	6.28±2.67	11.30	597.4±0.19	316.3±0.20	191.0±0.32	57.1±0.15	79.7±0.26
G	7.85±0.08	0.08±0.04	1.01±0.13	1.42±2.89	5.41±2.19	12.27	637.6±0.17	260.3±0.25	184.9±0.19	55.9±0.14	69.0±0.35
H	7.56±0.08	0.11±0.06	1.75±0.13	1.52±2.78	4.67±2.28	15.38	565.0±0.12	300.8±0.28	198.1±0.16	59.7±0.30	86.5±0.34
I	7.74±0.09	0.14±0.03	1.68±0.12	1.02±3.03	4.92±2.12	12.29	619.1±0.14	320.3±0.30	186.1±0.10	55.0±0.24	89.7±0.45

The increase in the content of organic matter (OM), nitrogen (N) and carbon (C), after the experiment was completed in the growing E, F, G, H, and I. This situation was due to the fact that it contained dried poultry manure, biochar and poultry manure compost. This growing media allowed the retention of nutrients in the soil and prevented their significant leaching and emission into the atmosphere. A similar situation was reported by Lehmann et al., (2007) where 2.5% biochar was added, allowing the soil to retain 12% more nitrogen than in soil without additives. However, Zhan et al., (2015) observed that the addition of biochar resulted in the retention of 27% more carbon and 75% more nitrogen than in the soil without any additives after the pot experiment was completed. When the carbon content increased, it could be related to roots which remained in the soil after the plants were removed from the pots. This situation can increase the results of carbon content. Also, in the research conducted by Dróżdż et al., (2020a), the increase in carbon content in the growing media after the plant growth was observed.

The pH of the soil mixtures did not change significantly. Only a decrease in pH can be observed in the growing medium D, in which 3 of 5 plants did not survive. Acidification of (<5) soil can negatively affect the assimilation of nutrients by plants and decreases the activity of microorganisms (Dyśko, 2019; Opole Agricultural Advisory Centre, 2021).

There was also a significant loss of sodium in all growing media. This is related to the fact that sodium is naturally rinsed and evaporates with water on the surface of the pot. It is not a key component for plant growth, but the excessive amounts of Na can cause inhibition of plant growth (Borkowski et al., 2014). Phosphorous can help to improve the absorption of carbon dioxide from the air and can help plant cells grow when the environment lacks potassium (K+S Minerals and Agriculture, 2019).

The results confirmed that the addition of the investigated soil enhancers, i.e., poultry manure derived biochar, dried poultry manure and compost resulted in a slower but more efficient way of dosing micro- and macro-nutrients. Plants that absorb micronutrients and macronutrients can achieve higher biomass growth parameters because the nutrients are not quickly decomposed and leached from the soil. This fact is also confirmed by Jarosz et al., (2022) who used fresh poultry manure and poultry manure derived biochar. They tested the soil properties before the plant experiment and after one and five years. They found that biochar had a positive effect on soil properties as a long-term fertilizer, while fresh poultry manure degraded much faster preventing the plant from realizing most of the fertilizer's potential.

However, figure 21 presents the percentage losses of individual nutrients in each growing medium which were analyzed after the plant growth experiment was completed.

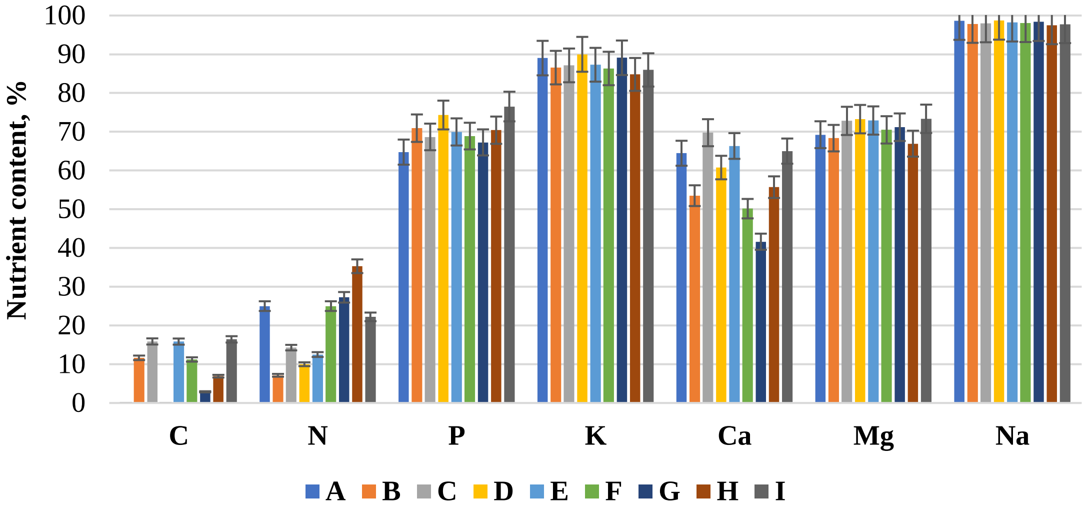

Fig.21. Percentage losses in the selected parameters of the investigated growing media.

Figure 21 presents the percentage losses of the main nutrients necessary for plant growth. Significant losses of 40-99% in K, Ca, Mg and Na content can be observed in all growing media. Soremi et al., (2022) observed similar conclusions regarding the use of poultry manure in soybean cultivation. The addition of poultry manure resulted in a significant increase in the content of C, N, P, K, Ca, Mg, while after the plant growth period the soil contained on average 20-90% less nutrients than at the beginning. However, the increase in the C/N ratio is due to improved availability of bioavailable forms of nitrogen for plants. The same conclusions were obtained by Jarosz et al. (2022) who observed higher nitrogen absorption from soil that was fertilized with poultry manure derived biochar. Thus, increasing the C/N ratio in the soil with the addition of biochar after a period of plant growth. In the experiment with cherry tomatoes, the values of pH of the growing media A, B, C, E, F and I increased by 1-6%. Chan et al. (2008) and Sikder and Joardar (2018) demonstrated that soil pH increased after adding poultry manure and poultry manure derived biochar. This was due to the fact that the poultry manure itself had alkaline pH which caused the soil to deacidify.

4. Characteristics of the collected cherry tomato plant biomass after the completion of the plant growing experiment

Collected cherry tomato plants were analyzed for the chemical composition. The obtained results are presented in table 33.

Tab.33. Chemical composition of the collected cherry tomatoes after the completion of the plant growing experiment.

Parameters	**N**	**C**	**C/N**	**Ca**	**K**	**Mg**	**Na**	**P**
Units	%		-	mg/kg				
Plant- A	2.01±0.02	36.94±0.01	17.83	3413.6±0.12	2696.6±0.34	384.6±0.35	397.4±0.12	553.1±0.43
Plant - B	2.13±0.02	37.15±0.02	17.46	2172.6±0.22	3009.2±0.43	364.2±0.36	497.2±0.12	519.4±0.34
Plant - C	2.18±0.02	36.02±0.02	16.49	2491.6±0.23	3369.6±0.42	358.8±0.22	530.6±0.12	595.2±0.45
Plant – D	4.82±0.02	36.41±0.01	7.56	2734.2±0.32	1894.6±0.32	368.2±0.21	439.2±0.43	260.8±0.43
Plant - E	3.25±0.02	37.20±0.03	11.45	1628.4±0.34	3842.2±0.237	326.8±0.45	625.4±0.23	386.8±0.45
Plant - F	2.63±0.02	37.56±0.02	14.27	1799.4±0.23	3958.6±0.43	339.6±0.43	496.6±0.35	517.4±0.34
Plant - G	2.62±0.04	38.18±0.02	23.51	2193.4±0.32	2339.6±0.225	276.8±0.42	226.4±0.46	350.8±0.46
Plant - H	2.07±0.03	36.86±0.03	17.79	1879±0.35	3683.8±0.23	356.1±0.25	621±0.42	421.2±0.32
Plant - I	2.30±0.02	36.81±0.01	16.03	1694±0.23	3198.8±0.32	327.2±0.43	383.4±0.35	379.4±0.22

According to the literature, plants should contain 3 to 4% nitrogen in above-ground tissues. Nitrogen in plants comes from fertilizers, growing media, nitrogen in the soil, nitrogen from the atmosphere and water. Microorganisms convert inorganic forms of nitrogen NH_4^+ and NO^{3-} into forms that are available by immobilization (Mosaic, 2022).

Chen and Chen (2020) tested green plants for C/N and C/P and the dependence of this value on the C/N and C/P of the growth medium. They found that the tested plants obtained the C/N of 9.3 and the C/P of 31.6. These values were strongly related to the growing medium in which they grew. A particular correlation between P and N can be observed in the plants from the growing medium D. P content was the lowest (260.8 mg/kg in dry weight) and N content was the highest (4.82%). Smith et al., (1987), Gniazdowska and Rychter, (2000), Güsewell, (2004) and Kumar et al., (2021), confirmed that N uptake by plants has a positive effect on plant growth, while P deficiency negatively affects N uptake and accumulation by the plant. This interaction is problematic when it is imbalanced, such as in the growing medium D cultivation where the P and C/N was the lowest in comparison to other growing media.

It can also be observed that the biomass of plants (aboveground part) from the growing media B, C, D, E, F, G, H, and I presented higher N content than the biomass of plants from the growing medium A (soil only). However, the biomass of plants from the growing media B, C, D, E, F, G, H, and I contained less Ca, Mg, Na and K than plants from the growing medium A. This relation can be due to the fact – according to Feng et al., (2020) – that plants absorbing nitrogen from soil low in this compound accumulate more nitrogen in their roots while Ca, Mg and Na ions are accumulated in plant biomass.

The opposite situation occurs when plants are grown in soil rich in nitrogen from growing media such as poultry manure. Then, the plant is not stressed by the deficiency of nitrogen which is necessary for the development of the root system and can distribute it homogeneously to the aboveground parts. Thus, resulting in a more significant increase in biomass. Similar conclusions were reached by Millard et al., (2007) confirming that nitrogen accumulation in plant roots is crucial when the soil is low in nitrogen, or it is more difficult to access it in winter due to low temperatures and limited ability of soil microorganisms and plants growth.

5. Composting of poultry manure for nutrient recovery (C, N, P)

The process of poultry manure composting was analyzed in detail to have better understanding of C, N and P cycles. This section presents the results of the laboratory composting study, including the characteristics of the composting mixtures and mature compost, microbiological analyses of poultry manure-based composts, mass balance of poultry manure composting for C, N and P and water balance.

5.1.Temperature evolution during composting

The temperature during the 40-day composting process was measured daily. During the composting process, the maximum value 61.2°C was observed in the composting reactor No. 1 and 60.1°C in the composting reactor No. 2. The maximum temperature values were observed on the 3rd and 4th day of the composting trial which is typical for proper composting. For example, Czekała et al. (2016) and Dróżdż et al., (2020a) observed the maximum increase in the temperature during the first 5 days from the start of composting. Figure 22 presents the temperature evolution during the 40-day composting process.

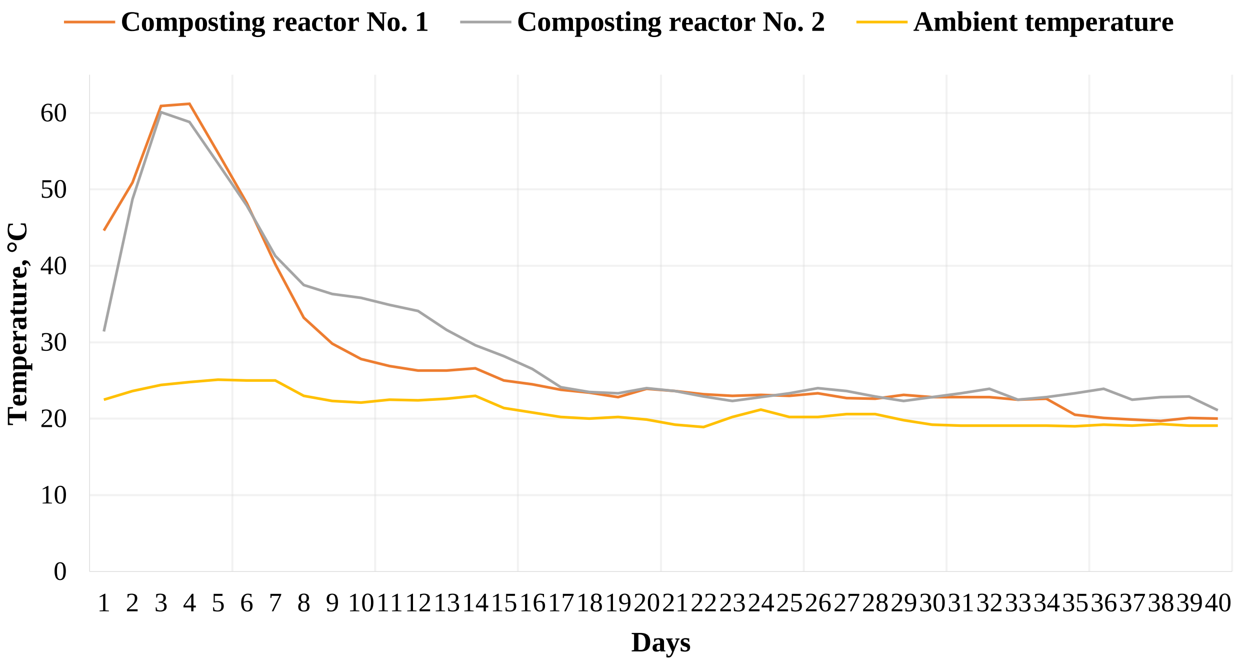

Fig.22. Temperature evolution during the 40-day composting.

Based on the temperature evolution, the composting process of poultry manure with wheat straw proceeded in a proper way – typical for laboratory composting in closed vessels with force aeration. The temperature >60°C obtained during the composting process also reduced the growth of pathogens. The temperature sufficient to reduce *Escheria coli* and *Salmonella* colonies is 47.5°C (Haug 1993; BioGreenhouse, 2016, Czekała et al., 2016; Dróżdż et al., 2020). Similar values were also obtained by Petric et al., (2008) who prepared compost from poultry manure and wheat straw. The highest value of the composting mixture was 64.6°C. After 3-4 days, the temperature dropped, and the composting mixture stabilized. They finished the composting process after 14 days, when the constant temperature was 30°C. Similar results were also obtained by Czekała et al. (2016) composted poultry manure with straw. They obtained the maximum temperature of 69°C, and the active phase of the process was completed after 28 days.

5.2. Changes in the selected properties of the composting mixtures

The composting mixtures were subjected to physicochemical analysis before the start, at the end of the 40-day of composting process and after 5 months of composts maturation. Table 34 presents the physicochemical analysis of the composting mixtures.

Tab.34. Physicochemical analysis of the composting mixtures prior to composting, after 40 days of composting and after 5 months of compost maturation.

Parameters	Units	Composting mixture from composting reactor No. 1			Composting mixture from composting reactor No. 2		
		Start	After 40 days of composting	Compost- After 5 months of maturation	Start	After 40 days of composting	Compost- After 5 months of maturation
C_{org}	%	46.66±0.14	45.12±0.11	43.51±0.16	46.33±0.11	42.42±0.19	41.03±0.12
N		2.89±0.01	2.66±0.02	2.43±0.02	2.35±0.04	2.32±0.03	2.21±0.11
P_2O_5	mg/kg	19.24±0.24	10.47±0.27	10.12±0.31	18.66±0.20	10.58±0.23	10.12±0.17
MC	%	64.50±2.19	65.10±2.14	37.49±1.22	63.29±2.41	66.24±2.44	28.25±2.37
OM		83.99±2.15	70.89±2.14	56.00±1.11	83.52±1.92	79.44±1.69	45.85±2.00
C/N	-	24.69	16.96	18.51	19.71	18.28	18.56
pH		6.89±0.13	9.19±0.11	8.61±0.14	6.80±0.17	9.12±0.12	8.77±0.12
EC	mS/cm	7.47±1.51	7.97±1.14	10.14±1.29	6.97±1.54	7.86±1.32	10.22±1.22

The contents of P_2O_5, MC, C/N ratio, pH, and EC increased during the 40 days of composting process. However, the content of N, P_2O_5, MC, C/N ratio, pH and OM decreased in the compost during the 5 months of the maturation phase. Only EC during the maturation of the compost increased. Khan et al., (2014) prepared a composting mixture from poultry manure, biochar and straw. They observed that the C/N ratio increased during the process, while it decreased during the maturation phase. However, EC decreased during the initial composting phase, while it increased during the maturation of the mixture, which lasted 126 days. Similar results were obtained by Hwang et al. (2020) who reported that nitrogen content decreased by

20-30%. Also, Ross et al., (2020) have concluded that carbon content during the composting process can be reduced by up to 60%. The total phosphorus content can be reduced by up to 50% (Ross et al., 2020). In the study by Petrica et al., (2009) they also investigated composting of wheat straw and poultry manure. They observed that the decrease in the content of organic matter was related to the use of organic matter for chemical and physical processes involving microorganisms. They also noted that pH increased after the composting process. However, it decreased slightly after the maturation period. The changes in pH were associated with the intense ammonia emissions, high process temperatures and dynamic decomposition of organic matter. Alkaline pH can have a beneficial effect on reducing ammonia emissions. It should be noted, however, that an excessively high pH (alkaline), according to Campbell et al., (1997), can inhibit plant nutrient uptake, leading to nutrient deficiencies and problems with proper plant growth.

The wet bulk density for composting mixtures of wheat straw and poultry manure was 260-275 kg/m^3 and the porosity was 60-62%. These are typical values for this kind of materials (Choi et al., 2001; Czekała et al., 2016; Janczak et al., 2017). Similar results were obtained by Janczak et al., (2017) who reported the wet bulk density of composting mixture (poultry manure and wheat straw) of 299 kg/m^3 and air-filled porosity of 75.6%.

5.3.Microbiological analysis of the obtained composts

The composting mixtures after the 40 days of composting sampled from the composting reactor No. 1 and 2 were tested for the presence and number of live eggs of intestinal parasites *Ascaris* sp., *Trichuris* sp., *Toxocara* sp. in the laboratory of JARS in Mysłowice (Poland). The analysis presented the absence of *Ascaris* sp., *Trichuris* sp., *Toxocara* sp.

The composting mixtures were also tested for the presence of *Escherichia coli* and *Salmonella* in the laboratory at the Czestochowa University of Technology (Poland). The analysis presented the absence of the *Escherichia coli* and *Salmonella*.

The Regulation of the European Parliament and of The Council (EU) 2019/1009 of June 5, 2019 allows soil enhancers *Escherichia coli* or *Enterococcaceae* in the permissible amount of 1000 CFU (Colony Forming Unit) in 1 g or 1 ml of test solution. On the other hand, it does not allow the occurrence of *Salmonella* spp. This research confirmed that the hygienization of the composts were performed properly and that temperatures above 60°C was sufficient for the reduction of pathogenic microorganisms (Alsanius et al., 2016). Effect of high temperature

(70°C), reduces *Salmonella*, within an hour from fertilizer products (Fertilizing Product Directive from July 16, 2022).

5.4. Heavy metal content in the obtained composts

After the composting process and 5 months of compost maturation, the composts from composting reactor No. 1 and No. 2 were analyzed for the content of selected heavy metals. The obtained results are presented in table 35.

Tab.35. Heavy metal content in the composting mixtures after the completion of composting process.

Heavy metals	Al	Cr	Cu	Fe	Mn	Pb	Zn	Cd	Co	Ni
Units	mg/kg									
Compost from composting reactor No. 1	294.16±0.02	-	7.3±0.04	377.17±0.05	123.48±0.04	-	129.71± 0.03	-	-	-
Compost from composting reactor No. 2	241.49±0.05	-	2.99±0.05	258.94±0.04	92.96±0.04	-	100.09± 0.02	-	-	-

The obtained results were compared to the regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization from 2007. The permissible values should not exceed for: chromium < 100 mg*kg^{-1} dry matter, cadmium < 5 mg*kg^{-1} dry matter, nickel < 60 mg*kg^{-1} dry matter, lead < 140 mg*kg^{-1} dry matter. The results obtained from the tests for the content of heavy metals confirmed that the composts did not exceed the permissible limits.

To assess the acceptable limits for Cu and Zn content, the Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending, Regulations was used (EC) No 1069/2009 and (EC) No 1107, update 16 July 2022. The Cu content in an organo-mineral fertilizer must not exceed 600 mg/kg dry matter, and the Zn content in an organo-mineral fertilizer must not exceed 1 500 mg/kg dry matter. The results obtained from the tests for the Cu and Zn confirmed that the composts did not exceed the permissible limits. Similar results were obtained by Amanullah et al., (2007) where the range for Mn was 190-380 mg/kg, Cu 24-172 mg/kg, Fe 930-1450 mg/kg and Zn was 90-460 mg/kg dry matter. It can be concluded that the reported data are within the typical range for poultry manure. According to Adekanmi

(2021), the content of heavy metals in poultry manure can be different depending on the breeding method (cage, free-range, litter), feed, type of poultry (laying hens, broilers).

5.5. Analysis of the condensate and leachate collected during composting

The 40-day composting of poultry manure generated leachate and condensate. Leachate and condensate were collected weekly from the containers, placed next to the composting reactors. The generation of significant amounts of leachate and condensate was observed especially during the first two weeks of composting due to the increase of temperature of the process. The collected leachate and condensate were analyzed for $N\text{-}NH_4$ and pH. Table 36 summarizes the results for weeks 1 and 2. In the following weeks, the quantities of leachate and condensate collected in the capturing system were negligible and insufficient for the analysis.

Tab.36. The analysis of leachate and condensate from composting.

Sample		Liquids	*$N\text{-}NH_4$	pH	Volume
			mg/dm^3	-	ml
First week	Composting reactor No. 1	Condensate	16.36±1.50	8.56±0.07	100
		Leachate	2.82±1.34	8.78±0.12	60
	Composting reactor No. 2	Condensate	25.76±1.40	8.68±0.08	150
		Leachate	2.23±1.23	9.09±0.07	55
Second week	Composting reactor No. 1	Condensate	19.60±1.52	8.86±0.10	50
		Leachate	2.25±1.65	9.34±0.09	49
	Composting reactor No. 2	Condensate	26.32±1.29	8.83±0.03	45
		Leachate	1.05±1.52	9.07±0.02	48

The increase in temperature during composting led to the evaporation of moisture contained in the composting mixtures. The increase in temperature and pH caused nitrogen in the form of ammonia to migrate to the upstream side of the composting reactor and condense as water vapor (condensate) and then moved downwards in the form of leachate. A higher value in the condensate means increased gas emissions (Janczak et al., 2017; Sanadi et al., 2019). However, in the case of poultry manure, these values are typical because it contains significant amounts of nitrogen. Janczak et al., (2017) observed that during composting of poultry manure with straw and biochar, ammonia was released in the first week at a level of 25-35 mg/dm^3. The researchers also noted that adding biochar to the compost reduced ammonia emissions by 30-40% compared to composting poultry manure and straw. Chowdhury et al., (2014) found that pH above 9 and temperature above 45°C promoted ammonia emissions from the composting reactors. Similar results during composting of poultry manure were obtained by Steiner et al. (2010), the highest ammonia content occurred on the 10th day of composting and exceeded 38 mg/dm^3. Also, Chowdhury et al., (2014) and Sanadi et al., (2019) have suggested that significant amounts of condensate and leachate can be used as liquid fertilizers.

However, additional analyses would have to be carried out to assess their fertilizing potential. In this study comparing weeks 1 and 2, the amount of leachate and condensate decreased, this was associated with a decrease in composting dynamics and a gradual decrease in temperature. However, it was noticeable that there was an increased activity of nitrifying microorganisms, which need several days to use nitrogen to oxidize ammonium and nitrate ions. Therefore, the obtained results of ammonia release from the condensate and leachate were higher only in the second week (Hao et al., 2008).

5.6. Gaseous emissions during composting

Composting of poultry manure is associated with significant gaseous emissions, in particular NH_3 and CO_2. Table 37 presents the results of weekly measurements of gas cumulative values from a five-week composting period.

Tab.37. Emissions of ammonia and carbon dioxide from composting process.

Unit, mg	NH_3				
	I week	**II week**	**III week**	**IV week**	**V week**
Composting reactor No. 1	10.43±2.03	9.22±1.93	2.66±2.13	3.63±2.33	3.89±2.89
Composting reactor No. 2	16.56±2.43	12.82±2.52	14.98±1.52	5.33±2.81	3.99±2.95
	CO_2				
Composting reactor No. 1	40.81±1.93	19.22±2.22	6.20±3.03	11.44±2.77	10.56±2.07
Composting reactor No. 2	32.62±2.67	12.84±2.89	7.91±2.81	9.39±3.01	12.15±2.43

Ammonia emissions increased between the second and third week when the composting mixture was removed and mixed for additional aeration and sampled for testing. The same situation occurred during the composting of poultry manure by Janczak et al., (2017) who mixed the composting mixtures on weekly basis. This activity also affects the emission of ammonia which increased within a day of placing the compost mixture back in the reactor. Carbon dioxide emissions were significantly reduced by additional aeration of the compost mixture during weekly mixing.

Ammonia emissions also decreased over time, with a slight increase a few days after the composting reactor No. 1 and No. 2 was opened. Shen et al., (2011), used different air flow from 0.01 to 0.2 m^3/min when composting poultry manure. They found that NH_3 emissions ranged from 40 to 100 mg/h in the first week. The emissions were higher when the air flow was increased. In the second week of composting process, ammonia emissions reached more than 200 mg/h after re-mixing the composting mixture. A similar experiment was conducted by Petric et al. (2009) who used poultry manure and wheat straw for composting. Ammonia emissions were higher in the second week (400 mg in dry weight) and decreased with the duration of the process. Carbon dioxide emissions were higher in the first week (7000 mg in dry weight) and decreased with the duration of the process (obtained less than 1000 mg in last day of composting process).

Beck-Friis et al. (2001) estimated that almost 98% of the nitrogen loss in the composting process is in the form of ammonia. Ammonia emissions from composting depend mainly on a substrate used in composting mixtures, temperature, moisture, pH, and carbon dioxide (Liang et al., 2004).

5.7. Mass balance for composting of poultry manure

To analyze the feasibility of composting of poultry manure for nutrient recovery, in particular C, N, P, the mass balance was calculated for composting of poultry manure in the composting reactor No. 1 and 2.

Based on the results obtained from analyzing solid samples of the composts and gaseous emissions the mass balances of nitrogen (TN), phosphorus (P_2O_5) and carbon (C_{org}) were calculated. The results are presented in table 38.

Tab.38. Mass balance for composting of poultry manure.

Parameters	Composting reactor No.1	Composting reactor No.2
Composting time (days)	40	40
Initial weight of the composting mixture, g (wet weight)	**13780**	**13640**
Final weight of the composting mixture, g (wet weight)	**4920**	**3620**
Mass of leachate and condensate, g (wet weight)	390	392
Mass of samples collected, g (wet weight)	320	308
Initial mass of organic matter, g (wet weight)	4390	5238
Final mass of organic matter, g (wet weight)	2526	2044
Initial mass of water, g (wet weight)	8680	7702
Final mass of water, g (wet weight)	1684	876
Nitrogen balance		
Initial nitrogen, g (dry weight)	395.93	320.54
Final nitrogen, g (dry weight)	121.03	80
NH_3 emissions, g (wet weight)	4.70	5.03
Other losses (leachate, condensate, NO_x emissions, etc.), g (wet weight)	240.2	235.51
Carbon balance		
Initial carbon, g (dry weight)	6429.75	6319.41
Final carbon, g (dry weight)	2140.69	1485.29
C-CO_2 emissions, g (wet weight)	7.03	6.23
Other losses (leachate, condensate, CH_4 emissions, etc.), g (wet weight)	4282.03	4827.89
Phosphorus balance		
Initial phosphorus, g (dry weight)	0.27	0.25
Final phosphorus, g (dry weight)	0.06	0.04
Other losses (leachate, condensate etc.), g (wet weight)	0.21	0.21

The initial mass of the composting mixtures decreased by 64.29 % and 73.46 % from the composting reactors No. 1 and 2, respectively. The weight loss was significant because both composts were matured for 5 months under laboratory conditions, and the water loss during this time was 81% and 88%, respectively. However, the loss of organic matter was 43% for the compost from reactor No. 1 and 60% for the compost from reactor No. 2. Tiquia et al., (2002) composted animal manure in a composting windrow and reported a compost mass loss of 57%. Composting in a windrow is slower and there are lower mass losses compared to composting in composting reactors under controlled conditions. Similar results were obtained by Petric et al., (2009) in which the mass of poultry manure compost after the process decreased by 62% and the loss of organic matter was estimated at 40-45%. Dach et. al., (2012) also investigated the mass balance of animal manure mixtures during composting. They observed a decrease in the mass of the compost mixture between 38 and 47%. Water losses from compost prepared from poultry manure, estimated by Ahn et al. (2007), reached about 40-65%. The increased aeration of the compost, the higher the water losses.

The mass of nitrogen decreased by 69% and 75% in the compost from the composting reactors No. 1 and 2, respectively. Dach et. al., (2012) composted animal manure in the laboratory reactors and reported that the content of nitrogen which decreased by 7-9% and NH_4 emissions by 92.72% in comparison to the initial values. Ogunwande et al. (2008) who composted poultry manure also obtained similar results. They reported nitrogen losses of 60-80%. Awasthi et al., (2020) composted poultry manure with the addition of biochar which reduced nitrogen losses by 10%. Only 38-41% was emitted from the composting reactors in the form of ammonia.

In this study the initial mass of carbon decreased by 66.7% and 76.49% in the composting mixtures from the composting reactor No. 1 and 2, respectively. Carbon dioxide emissions during the composting process of poultry manure were analyzed by Hwang et al., (2020). The researchers observed a significant increase in CO_2 emissions at the beginning of the composting process when the microbial activity was significant. The emissions of CO_2 amounted to 1016 g/kg of wet weight. Similar results were also obtained by Tiquia et al., (2002), who composted animal manure in a windrow, carbon losses were at 50-63%. Awasthi et al., (2021) composted poultry manure in a compost reactor and reported the carbon losses as CO_2 at 47%.

The content of phosphorus in the final mass of the composting mixtures from the composting reactors No. 1 and 2. decreased by 77.78% and 84%, respectively. Similar results were also obtained by Tiquia et al, (2002) who composted animal manure in a windrow, and phosphorus losses were 53%. High phosphorus levels were observed by Ogunwande et al. (2008) who composted poultry manure. The phosphorus losses ranged from 40-67% during composting of poultry manure. In the study of Zhang et al., (2021) it was confirmed that phosphorus can be characterized in animal manure-based composts in the form of $MgNH_4PO_4$ - $6H_2O$ crystals. The different forms of phosphorus in compost have an impact on the microbial population structure during composting. Therefore, phosphorus losses can be associated with intensive phosphorus utilization by microorganisms.

In summary, the literature reports numerous studies on the composting process, including composting of poultry manure, but still a more comprehensive approach is needed when it comes to analyzing the C, N and P cycles during the process to prevent from excessive nutrient losses and to allow nutrient recycling.

VI. Summary and conclusions

Poultry manure is a valuable resource which demonstrates high fertilizing potential. Raw poultry manure can be spread on agricultural fields in the quantities within the permissible limits. However, the excess of poultry manure – due to the physicochemical properties – needs to be handled and managed with the processing methods which would assure the efficiency in recovery of nutrients (C, N, P) and limit the risks related to various contaminants present in poultry manure, and thus to prevent from the contamination of soil and entering food chain.

Processing methods which allow conversion of poultry manure to value added products with high fertilizing potential can include drying, composting and pyrolysis. These methods allow conversion of raw poultry manure into stable materials which can be easily stored, transported, mixed with soil, and distributed in the agricultural fields. With the introduction of new legislation on fertilizing products (i.e., Fertilizing Product Directive from July 16, 2022) it is expected that the interest in such resources as poultry manure to be used as substrates to obtain e.g., soil organic enhancers will increase. Poultry manure-based soil enhancers could – after fulfilling the conformity assessment – become available on the EU market. This opens more possibilities for the countries with high poultry production, and thus significant quantities of poultry manure to be managed.

Therefore, the results from this research work can contribute to the advancement of the state of the art by providing a better understanding of the properties of soil enhancers derived from poultry manure, in particular biochar derived from poultry manure, and their effects on soil properties and plant growth.

In view to the obtained results the formulated hypotheses have been confirmed and the following conclusions have been drawn.

1. **Soil enhancers prepared from poultry manure by composting, pyrolysis and drying of poultry manure demonstrated the following properties:**

Conclusion 1. Microbiological analysis of fresh poultry manure confirmed the lack of risk related to the occurrence of pathogenic microorganisms, i.e., *Salmonella, E. coli* or eggs of parasites. Also, no significant amounts of heavy metals exceeding the legal limits were found in the poultry manure.

Conclusion 2. Poultry manure derived biochar as a soil enhancer had a high pH of 12-13 compared to the EBC requirements for plant biomass biochar of 6-10. The biochar obtained at 475°C had the lowest pH among the other biochars (from temperatures 575, 675 and 775°C), below 12.55. The biochar from 475°C was also characterized by the relatively high organic matter content of 39.47% and nitrogen content of 3.73%, while it had the lowest C/N ratio of 8.18. According to the recommendations of the EBC, biochar obtained at 475°C has the most beneficial parameters in terms of fertilizing potential.

Conclusion 3. Poultry manure composts after 5 months of maturation were characterized by pH for compost from composting reactor forms No. 1 and 2, 8.61 and 8.77, respectively. The content of organic matter of the composts from the composting reactor No. 1 and 2, was 55% and 45.85, respectively. The EC of both composts was 10.14-10.22 mS/cm. The nitrogen contents of the composts from the composting reactor No. 1 and 2, were of 2.43% and 2.21%, respectively. After 5 months of maturation, both composts were ready to be used as soil enhancers.

Conclusion 4. Drying of the poultry manure caused the decrease in pH in comparison to the raw poultry manure from 7.51 to 7.01. The moisture content was reduced by 93% and the organic content decreased by 8%. However, the N content of the dried poultry manure did not change significantly and amounted to 7.91%.

2. Composting of poultry manure:

Conclusion 5. The composting temperature above 60°C enabled hygienization and reduced the growth of microorganisms, i.e., *Salmonella* and *Escherichia coli.* The 40-day composting allowed the C/N ratio to decrease from 24.69 to 16.96 for the composting mixture from the composting reactor No. 1, and 19.71 to 18.28 for the composting mixture from the composting reactor No. 2. The nitrogen content of the composting mixture from the composting reactor No. 1 and 2 was also reduced by 7.96% and 1.28%, respectively. Water content compared to the start of composting and after a 5-month maturation period decreased by 81% and 82% for the composts from the composting reactor No.1 and 2, respectively.

Conclusion 6. During the composting process of poultry manure there was an intensive reduction of nitrogen present in the leachate, condensate and in gaseous as ammonia and carbon dioxide. The mass of nitrogen decreased by 69% and 75% in the composts from the composting reactors No. 1 and 2, respectively. The condensate and leachate that was generated from the composting reactor No.1 and 2 can be managed as a liquid fertilizer. During the 40-day composting period in composting reactor No. 1 and 2, 390 g and 392 g of leachate and condensate were generated, respectively. The pH ranged between 8 and 9.

Conclusion 7. During the composting process of poultry manure, the initial mass of carbon decreased by 66.7% and 76.49% in the composting mixtures from the composting reactor No. 1 and 2, respectively. The content of phosphorus in the final mass of the composting mixtures from the composting reactors No. 1 and 2. decreased by 77.78% and 84%, respectively.

3. Effect of growing media on soil properties and plant growth:

Conclusion 9. Adding biochar to the growing media G, H, I resulted in an increase in pH (7.55-8.00) compared to the growing medium A (6.99) used as the control. Adding the obtained composts to the growing media B, C, E, F, H, and I resulted in an increase of 43-65% in organic matter, 42-60% in N, 40-60% in C, and 37-66% in P compared to the growing medium A. The addition of dried poultry manure resulted in an 8% decrease in C/N in the growing medium D compared to the growing media A (control). The addition of poultry manure to the growing media D, E and F resulted in a 2-2.2% increase in K content, compared to growing medium A (control).

Conclusion 10. In the growing medium F, plant biomass was the largest among the other growing media, i.e., 56 g wet weight and 3.61 g dry weight. In terms of height, however, the tallest plants were collected from the growing medium H and the height was 65.4 cm. The application of the growing medium D caused difficulties in the growth of cherry tomatoes. Only 2 out of 5 plants grew. The excessive ammonia emissions from growing medium D can inhibit plant growth. Ammonia emissions change the pH of the rhizosphere, thereby affecting the diversity of microorganisms in the soil and their interactions with plants. The pH in the growing medium D was 6.82 and in the other growing media it was in the ranged of 7.5-7.7. Also, the plants grown in the growing medium D accumulated almost 58% of nitrogen, while the rest of the plants from growing media A, B, C, E, F, G, H, and I only 15-20%.

Conclusion 11. In all investigated growing media after the plant growth period the reduction in the content of K, Ca, Mg and Na content by 40-99% was observed. The content of C, N, P in all growing media after the plant growth period, contained on average 20-90% less nutrients than at the beginning. In the growing media D, F, G, H, and I were an increase in C/N by 10-63%. The increase in pH by 1-6% were observed in all growing media with the addition of poultry manure.

The results of the study have provided an insight into the nitrogen, phosphorus, and carbon cycles in the process of poultry manure composting and the losses that are observed during the process. Despite the fact that the literature reports a number of studies on composting of poultry manure, there is a need for better understanding of C, N and P cycles during the process and associated losses of these nutrients. Also, there is a majority of studies from the literature that focus on gaseous emissions, while composting byproducts such as leachate and condensate are neglected. It is recommended in order to know the C, N, and P cycle that occurs during the composting process, in terms of input and output products, but also including leachate and condensate. Leachate and condensate are also rich in nutrients, which, after physicochemical analyzes, can be used as liquid fertilizers, according to the Fertilizing Product Directive.

Fertilizing Product Directive (Regulation-EU, 2019/1009), which came into force on July 16, 2022, provides an opportunity to expand the market for fertilizing products, in particular with soil enhancers based on poultry manure. A more comprehensive approach to management of poultry manure by drying, pyrolysis and composting is an alternative to using only raw poultry manure in plant cultivation. Poultry manure derived biochars and composts are microbiologically safe, environmentally safe in terms of heavy metals, and with no significant emissions, especially of ammonia and carbon dioxide.

Further research on the potentials of poultry manure to produce soil enhancers should include an overall assessment of the environmental and economic impact of applying poultry manure derived soil enhancers to close the C, N and P cycle as well as the effects on different types of soils under various climatic conditions and selected plants.

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Appendices

1. The list of all tables included in the dissertation is presented below:

Table

2. The list of all figures included in the dissertation is presented below:

Figures