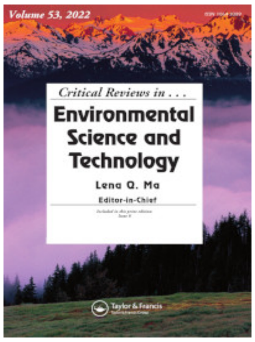

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Cycles of carbon, nitrogen and phosphorus in poultry manure management technologies – environmental aspects

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Cycles of carbon, nitrogen and phosphorus in poultry manure management technologies – environmental aspects

Małgorzata Kacprzak[a], Krystyna Malińska[b], Anna Grosser[b], Jolanta Sobik-Szołtysek[b], Katarzyna Wystalska[b], Danuta Dróżdż[b], Anna Jasińska[b], and Erik Meers[c]

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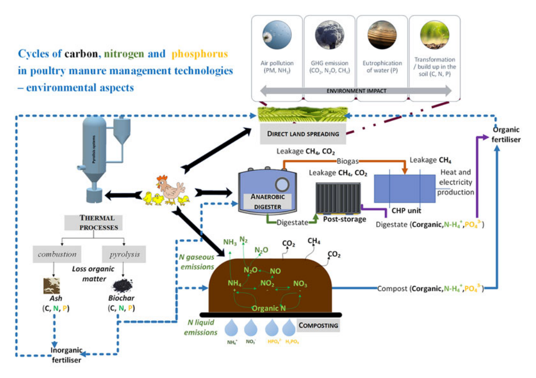
ABSTRACT



Poultry manure (PM) has become a serious environmental problem due to large scale of industrial production and unsustainable management, causing emissions of greenhouse gases (GHGs), odors, leakage of nutrients as well as inorganic, organic and biological pollutants. The main goal of this review was to get a better understanding of carbon, nitrogen, and phosphorus cycles in processing of poultry manure with the most common technologies such as composting, anaerobic digestion, or thermal processes, e.g. pyrolysis. The carbon contained in organic matter (ca. 31%) is mineralized and humified under aerobic conditions (matter recovery) and/or converted into biogas under anaerobic conditions (energy recovery). PM as a feedstock for pyrolysis to obtain biochar may effectively store and prevent C, thus contributing to climate change abatement. During composting, nitrogen is reduced from the compost mixture by leachates in the form of NH_4^+, NO_3^- or gaseous emissions of NH_3, N_2O, N_2. The C/N ratio is also decisive parameter. Most environmental threats of unmanaged PM result from ammonia and nitrous oxide emissions, being higher for PM compared to cattle and cow manure independently of technological processes. The phosphorous in PM is mainly inorganic (32-84%). Using untreated manure as a fertilizer does not allow taking up high doses of phosphorus contained in poultry manure, so the excess accumulates in the soil and then leaches into groundwater. Biochar and struvite are an alternative to storage and source of high concentrations of phosphorous. Cycles of carbon, nitrogen and phosphorus are an integral effect of technologies used for PM management.

KEYWORDS Carbon sequestration; circular agriculture; greenhouse gas emission; nitrogen; phosphorous; poultry manure

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1. Introduction

Poultry production is estimated at 40% of the total meat consumption with the biggest producers in 2020: USA (23 million Mg), China (20 million Mg) and Brazil (16 million Mg), (USDA, 2021). Almost 20% of poultry meat within EU-27 countries is produced in Poland (Eurostat, 2021).

Poultry manure (PM) contains about 3-5% nitrogen, 0.9-3.5% phosphorus, and 1.5-3% potassium (Jędrczak et al., 2014). Moreover, the content of calcium, magnesium and sulfur is much higher than in cattle or pig manure (Bolan et al., 2010; Brassard et al., 2018). PM can be directly spreading on soil or treated by different processes to produce added-value products (compost, digestate, biochar). Soil application of PM initiates a series of reactions such as decomposition, hydrolysis, ammonia volatilization, nitrification, denitrification, fermentation and finally could be important source of GHGs: ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O), nitric oxide (NO) and carbon dioxide (CO_2), Li at al. (2012). Moreover, can lead to soil/groundwater contamination by heavy metals - Zn, Cu (Liu et al., 2020). The buffer capacity of the ecosystem may be exceeded and the fertilizer or long-term stored PM become an environmental hazard (Kabelitz et al., 2021). Therefore, any PM processing technology should be based on a thorough analysis of the nutrients (especially C/N/P, properly calibrated application methods based on biogeochemical cycles to prevent GHGs emissions and efficiently use the nutrients for soil improvement. Composting and anaerobic digestion (AD) are biotic-based, however strictly controlled by abiotic factors as temperature, moisture, redox potential, pH, substrate concentration gradient (Li et al., 2012). Biogas production from PM and use of the digestate as an organic fertilizer as renewable energy production and substitution of the mineral fertilizers led to the decrease of GHGs emissions (Kreidenweis et al., 2021). However, improperly processing results in an increase GHGs emissions, mainly due to high ammonia volatilization in the initial step of process.

Thermal conversion of PM is also considered as renewable energy source. The energy obtained is CO_2 neutral and saves fossil fuels (Billen et al., 2015). The life cycle assessments shown that thermal processing of PM generates less GHGs than direct land application and AD (He et al., 2022). Moreover, the solid post-process residues (ash, biochar) enable their environmental use as soil improvement (Piash et al., 2022).

The overall goal of this study was to analyze the current state of the art on biogeochemical cycles of carbon, nitrogen and phosphorus in the most common technologies poultry manure management such as land spreading, composting, anaerobic fermentation, combustion, gasification and pyrolysis in the context of environmental threats and climate changes mitigation.

2. Technologies for management

2.1. Mechanical

2.1.1. Landspreading

Traditionally PM has been used directly as a soil fertilizer (Table S1, supplementary material). Proper use led to the increase of biomass production and crop quality due to the content of minerals, such nitrogen and phosphorus. However, inappropriate use affected soil and plant quality and contaminated surface and groundwater by potentially toxic elements (PTEs), including cadmium, chromium, nickel, cobalt, copper, barium, lead, (Muhammad et al., 2020). Moreover PM could be a significant source of pathogens. In Australia 100% of broiler litter was contaminated with *Actinobacillus* and *Salmonella* and in the US - with *Escherichia coli* resistant to amoxicillin, ceftiofur, tetracycline, and sulfonamide (Kyakuwaire et al., 2019).

2.2. Biological

2.2.1. Composting

During PM composting, mineralization, nitrification, incomplete denitrification, and the release of gaseous occur. It follows various phases, i.e. mesophilic, thermophilic (dynamic biological processes involving microorganisms), cooling, and finally the compost maturation. The process requires adequate moisture, a C/N ratio, and the porosity of the compost mixture. To meet these conditions, the manure must be mixed with appropriate bulking materials such as sawdust, grasses, various types of straw, wood shavings, and chips. The temperature of the compost mixture should exceed 55°C and reach 70°C for the hygienization (EU Regulation No 142/2011). This applies, inter alia, to the degradation of live eggs of *Ascaris* sp., *Trichuris* sp., *Toxocara* sp., bacteria *Salmonella* and *Escherichia coli*. The pathogens number can be reduced after reaching high temperatures however requires strict monitoring (Lim et al., 2020). Aeration of the compost mixture is crucial and the minimum 15-20% O_2 is necessary. Lower values may cause the formation of anaerobic zones and contribute to the putrefaction of the mixture, thus hindering the proper functioning of microorganisms. The processing time may be 4-40 weeks, and the final weight of the compost will be reduced by 40-50% in relation to the initial weight. During composting nitrogen, carbon and phosphorous are partially lost: 13-70% for nitrogen, 42-62% for carbon and 28-50% for phosphorus (Hao & Benke, 2008; Harrison, 2008). Nitrogen is lost through leaching of NH_4^+, NO_3^- or releasing gaseous emissions of NH_3, N_2O, N_2. Carbon is lost in the form of CO_2, CH_4 and phosphorus mainly in the leachate of HPO_4^{2-} and H_2PO_4.

Bacteria and fungi are essential for composting. The most common bacteria in the compost mixture includes *Pseudomonas*, *Xanthomonas*, *Actinobacteria*, *Nocardi*a, *Streptomyces* which can break down organic matter. *Nitrosomonas* and *Nitrospira* specializing in nitrogen transformation are especially important for composting poultry manure. The fungi such *Aspergillus, Acremonium, Chrysosporium, Fusarium, Mortierella, Penicillium* and *Trichoderma* occur partially in the first and dominate the last stages of composting. Fungi occur in the mesophilic phase and during compost maturation where the temperature is not as high as in the active phase during which it can reach 50-60 °C (Sánchez et al., 2017).

Compost from PM has a positive effect on reducing soil evaporation, enriches soil with nitrogen, improves the release of nutrients, plant biomass and quality (Al-Bataina et al., 2016; Faucette et al., 2004). For example, the increase starch content of cassava as well as the oil and protein from mustard seeds was observed when plants were cultivated on soil fertilized by PM compost (Amanullah et al., 2010).

The mineralization causes changes in the organometallic complex of heavy metals. The ligands are transformed into forms of ligands with oxygen, i.e., carboxylic or hydroxyl complexes, which affect the mobility of particles and the possibility of their accumulation in living organisms.

2.2.2. Anaerobic processes

Anaerobic digestion (AD) is a complex biochemical process of macromolecular organic substances decomposition contained under anaerobic conditions (ORP<-200mV). Transformations allow for the conversion of biodegradable organic matter mainly into methane and carbon dioxide (Gallert & Winter, 2005) and reduction of nitrate and sulfate to hydrogen sulfide and sulfide, as well as anaerobic ammonification. The overall process of AD can be described by the equation (1) proposed in 1952 by Buswell (Anukam et al., 2019; Meegoda et al., 2018):

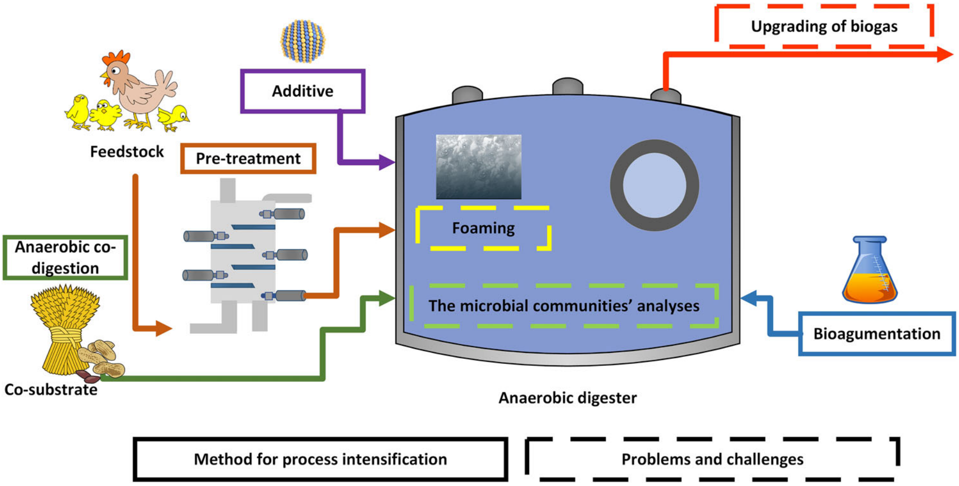

Figure 1. Key issues of research regarding AD of poultry manure, based on (Khoshnevisan et al., 2021).

$$C_cH_hO_oN_nS_s + \left(\frac{4c-h-2o+3n+2s}{4}\right)H_2O \rightarrow \left(\frac{4c-h+2o+3n+2s}{8}\right)CO_2 + \left(\frac{4c+h-2o-3n-2s}{8}\right)CH_4 + nNH_3 + sH_2S \quad (1)$$

Based on the biochemical reaction formula and the elementary composition of raw chicken manure (C (35.16%), H (4.83%), O (30.12%), S (0.84%), and N (5.44%)), Qioa et al. estimated that degradation of 1 kg of volatile solids (VS) of chicken manure produced

0.74 m^3 biogas, 0.42 m^3 methane and 72 g of ammonia nitrogen (87 g free ammonia nitrogen (FAN)) (Shapovalov et al., 2020).

AD is often limited by low C/N ratio, high content of nitrogen, hydrogen sulfide in biogas as well as problem with foaming (Figure 1). Optimization and improvement of anaerobic digestion efficiency is achieved by feedstock pretreatment before introduction to the digestion chambers and/or co-digestion of poultry manure with other organic waste (Dróżdż et al., 2020; Khoshnevisan et al., 2021; Kreidenweis et al., 2021). Bioaugmentation and the use of additives in the form of nanoparticles or trace elements supplementation also seem to be an promising option (Aguilar-Moreno et al., 2020; Hassanein et al., 2019; Shah et al., 2021) Furthermore, to reduce the risk of failure of the process due to ammonia accumulation, the following solutions can be applied: i) stripping (Guštin & Marinšek-Logar, 2011); ii) addition of ion exchange/adsorption materials such as e.g., zeolite (Ziganshina et al., 2015), natural chabazite (Lin et al., 2016) or biochar (Ma et al., 2021; Pan et al., 2019); iii) membrane separation (Wang et al., 2018); d) dilution of the feedstock (Duan et al., 2018). Table S2 (supplementary materials) summarizes some results of AD of poultry manure within the above-mentioned solutions.

2.3. Thermal

2.3.1. Combustion

The mostly used PM thermal process is combustion and co-combustion (Junga et al., 2017, Florin et al., 2009), where organic compounds are oxidized with the release of large amounts of heat (Figure 2). The process produces gases such as sulfur dioxide, nitrogen oxides, carbon dioxide, hydrogen chloride and ash. The use of the scaffold technology requires good technical solutions due to high ash content in PM and its low melting point (Kelleher et al., 2002). While the fluidized bed technology enables the reduction of nitrogen oxide emissions (Florin et al., 2009).

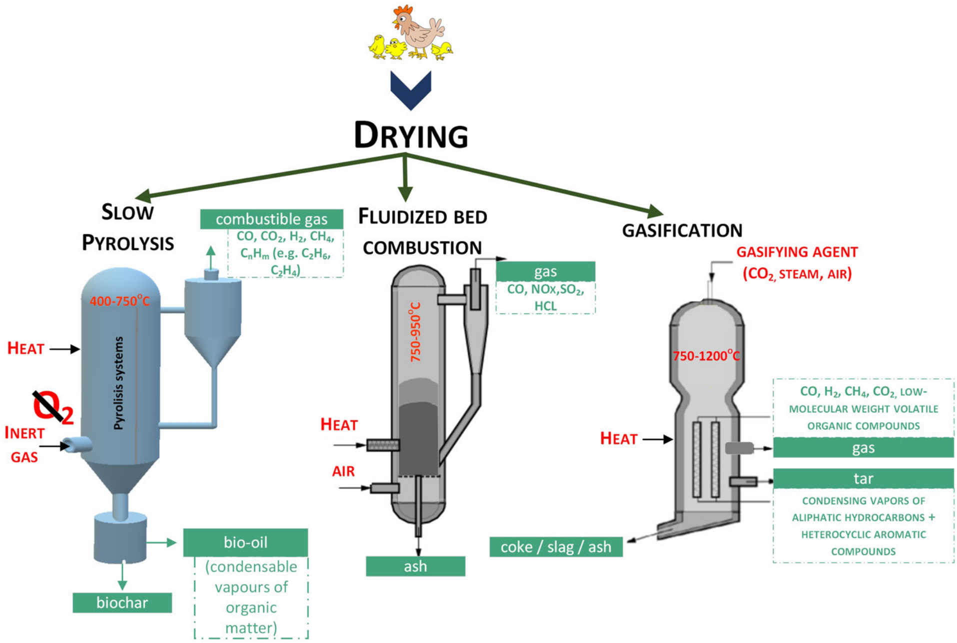

Figure 2. Possibilities of thermal conversion of poultry manure based on own study.

Usually, before combustion, gasification or pyrolysis, manure is pre-prepared by drying (Tańczuk et al., 2019a) which increase its caloric value from 2.6 to 13.5 GJ Mg^{-1} (Kelleher et al., 2002).

The ash generated by fluidized combustion is odorless, sterile and dry. It can be used as a fertilizer or a soil improver due to the desired phosphorus and potassium content (Billen et al., 2015, Kaikake et al., 2009, Luyckx et al., 2020). Therefore, it can also be used as additive for fertilizers or even chicken feed (Blake & Hess, 2014).

2.3.2. Gasification

PM gasification (Figure 2) is usually carried out in 1000°C in presence of oxidizing agents (e.g. air, oxygen, water vapor). In result, gaseous products mainly hydrogen and carbon monoxide, methane, carbon dioxide, nitrogen and water vapor are creating (equations 2-9) (Wielgosiński, 2016):

$$C+\frac{1}{2}O_2 \rightarrow CO+q \tag{2}$$

$$C+O_2 \rightarrow CO_2+q \tag{3}$$

$$C+2H_2O \rightarrow CO_2+2H_2-q \tag{4}$$

$$C+H_2O \rightarrow CO+H_2-q \tag{5}$$

$$C+2H_2 \quad \rightarrow CH_4+q \tag{6}$$

$$CO+H_2O \rightarrow CO_2+H_2+q \tag{7}$$

$$CO+3H_2 \rightarrow CH_4+H_2O+q \tag{8}$$

$$C + CO_2 \rightarrow 2CO - q \tag{9}$$

Thermal decomposition can be summarized (equation 10):

$$C_x\ H_yO_z\,heat\,CO_2 + H_2O + CO + CH_4 + C_2H_6 + CH_2O + \ldots + C_mH_n + \mathrm{C} - \mathrm{q} \tag{10}$$

These chemical reactions are both exothermic and endothermic. Solid residues in the form of ash or slag are also produced. The PM gasification is often analyzed in the option of co-gasification with biomass of plant origin. However, process is rather limited to laboratory and small-scale applications (Tańczuk et al., 2019a) due to technical problems and low quality of the gas produced (Tańczuk et al., 2019b). However, comparing to the gasification of fossil fuels the negative environmental impacts of this process (i.e. greenhouse effect) is reduced (Jeswani et al., 2019).

2.3.3. Pyrolysis

Pyrolysis is a process of transformation of organic matter under anaerobic conditions at high temperatures up to 1000° C (Wielgosiński, 2016) (equation 11):

$$C_x\ H_yO_z\,heat\,CO_2 + H_2O + CO + CH_4 + C_2H_6 + CH_2O + \ldots + C_mH_n + \mathrm{C} - \mathrm{q} \tag{11}$$

The liquid products of pyrolysis are mainly a mixture of oils, tars and water with dissolved simple aldehydes, alcohols and organic acids (Figure 2). Moreover, gases, such hydrogen, methane, ethane and their homologues, carbon monoxide and dioxide, and compounds such as hydrogen sulfide, ammonia, hydrogen chloride, and hydrogen fluoride are produced (Wielgosiński, 2016). Solid products containing mainly carbon (Wielgosiński, 2016) are referred to as biochar. Pyrolytic technologies are not as widely used on an industrial scale as is the case of combustion. In the effect the pyrolysis of PM biochar which can be used as a soil improver is produced (Mickan et al., 2016). Moreover, bio-oils can be a potential substrate for bio-grease production. The so-called slow pyrolysis (Ibarrola et al., 2012) during which metals are immobilized and phosphorus is made available, is recommended for the production of biochar (Roberts et al., 2017, Kleemann et al., 2017). Process efficiency is determined by the type of substrate being converted and the temperature of pyrolysis (Bavariani et al., 2019).

PM thermal processing ensures the sanitary safety of post-process products (Maj et al., 2022), (Figure 2) and eliminate potential risk of infection during direct land application (He et al., 2022). The presence of antibiotics or heavy metals in the PM does not interfere with thermal processes. However, the high content of chlorine and alkali metals in the ash can generate many problems, such as high-temperature corrosion, deposit formation on boiler heating surfaces and bed agglomeration in fluidized bed boilers (Maj et al., 2022).

3. Carbon cycle

3.1. Mineralization and humification under aerobic conditions

The 31% of PM is organic matter (Morvan et al., 2021). Mineralization and humification are fundamental for carbon, nitrogen and phosphorous cycles under aerobic conditions. Firstly organic matter is fragmented by invertebrates, chemically degraded, and organic substances are leached (Morgado et al., 2018). Then, during chemical reactions, microorganisms converted the C structures of complex organic molecules toward simpler generally soluble compounds (e.g., carbohydrates, proteins, amino acids) (Morgado et al., 2018). Some of them immediately transform during the primary mineralization process into soluble inorganics and/or gaseous (Figure S1, supplementary material). Simultaneously, the slower humification begins and the formation of complex molecules of colloidal nature and dark color called humus. During humification through several oxidation and hydrolysis reactions - humic acids, fulvic acids, hymatomelanic acids, and humins are created. C:N ratio of initial feedstock material play a crucial role in the process of carbon fixation associated with enzymatic activity and microbial variation. Products contain higher C, H and lower O compared to the original fresh residues, thus are more stable and resistant to decomposition (Morgado et al., 2018). The C/N value of 17.3 significantly enhanced the composting efficiency and the plant germination index (23.7%) compared to the C/N ratio 9.61, (Liu et al., 2020). Moreover, the suitable C/N ratio increased the relative abundance of Bacilli which played an important role during the mesophilic and thermophilic phases. Bacilli abundance was related to cellulose and β-glycosidase activities, thus improved fiber degradation and humification.

During the secondary mineralization the humus can be partially lost. Addition of thermally treated montmorillonite (M-) and illite (I-) improved the humus formation (Pan et al., 2021) . Furthermore, structural equation model and variance partitioning analysis demonstrated that M- and I- treatments promoted precursors to synthesize humic acids (HA) by coordinated regulation of biotic and abiotic pathway and to increase of HA content in the M- and I- treatments mainly through the abiotic pathway.

Microbially dependent mineralization is divided into three stages (Islam et al., 2021): i) an initial with typically present bacteria such *Bacillus*, *Clostridium*, *Proteus* and lactic acid bacteria; ii) an intermediate stage with more specialized *Bacillus, Pseudomonas, Acinetobacter, Arthrobacter, Enterobacter* and iii) last stage when the one-carbon-compound-oxidizing bacteria and other specialists release CO_2 from the most refractory of the organic residues. Kinetics of PM mineralization in soil depends on the type of manure. Higher CO_2 emissions (800 mg C kg^{-1}) were found in soils amended with hen poultry manure (PMH) as compare to broiler poultry manure (PMB) – 600 mg C kg^{-1} (Martín José et al., 2012). Moreover, application of different doses of solid and liquid fermented poultry manure significantly influenced the CO_2 emission from treated soils (Sathya & Maheswari, 2017).

3.2. Conversion into biogas under anaerobic conditions

Anaerobic digestion (AD) generally is divided into four phases such as hydrolysis, acidogenesis, acetogenesis (acetogenesis), and methanogenesis (Figure S2, supplementary materials). During technical scale, AD is divided into two phases: acidic (includes hydrolysis and acidogenesis) and methane (acetogenesis and methanogenesis) (Anukam et al., 2019; Issah et al., 2020).

Phase I - hydrolysis - in which water-insoluble organic polymers such as proteins, lipids, and carbohydrates are decomposed into simple, soluble monomers by extracellular enzymes (hydrolases e.g., proteases, lipases, cellulases, amylases) released by hydrolytic bacteria. The products of hydrolysis are amino acids, simple sugars, hydroxy-alcohols (main glycerol), and long-chain fatty acids (LCFAs) (Sahota et al., 2018). However, only 50% of the organic matter contained in the feedstock is broken down in this phase. This is linked with a lack of suitable enzymes for their degradation. (Meegoda et al., 2018).

The presence of lignocellulosic material in PM (e.g., straw, wood shavings, rice husk) is the bottleneck of this stage. Generally, lignocelluloses consists of three polymers: cellulose, hemicellulose, lignin and various inorganic materials (Bhatnagar et al., 2022). The proportion of each component depends on the manure type, the region and, consequently, the digestibility of fiber by the animals live in different parts of the world (Orlando & Borja, 2020, Table S2 supplementary material). Hemicellulose fractions are easily hydrolyzed into simple sugars. However cellulose and lignin are more difficult to degrade (Ferraro et al., 2020; Matheri et al., 2018). Lignin hydrolysis is a complicated process mainly due to the numerous carbon and ether bonds between phenolic alcohol derivatives (the basic monomers are trans-p-coniferyl, trans-p-coumaryl and trans-p-sinapyl alcohol). Furthermore, lignin surrounds hemicellulose and cellulose and forms a barrier that limits enzyme accessibility. The breakdown of polysaccharides become hampered (Cai et al., 2021; Orlando & Borja, 2020; Paritosh et al., 2021; Shrestha et al., 2017). Therefore, a pretreatment is essential to solubilization and degradation of the substrate with a significant content of recalcitrant lignin, such as PM (Figure S3, suplementary material). To accelerate the hydrolysis process after pretreatment of animal manure can be used: i) repture the crystalline structure of cellulose fraction; ii) increase the digestibility of the feedstocks owing to the reduction of particle size; iii) increase of lignocellulose materials porosity; iv) solubilization of hemicellulose; v) distruption of hemicellulose; vi) depolymerization of hemicellulose; vii) deacylation of hemicellulose; viii) alteration of lignin structure; ix) breakdown of lignin; x) hydrolization of fibrus proteins (e.g., keratin); xi) split complex polimer (Orlando & Borja, 2020, Reyes et al., 2021). Also, pretreatment of poultry manure before AD, via enzymes such as peroxidase and laccase enhance the rate of hydrolysis (Bhatnagar et al., 2022).

Phase II – acidogenesis - in which, facultative and obligate acidogenic bacteria convert the products of the hydrolysis to low-molecular organic compounds, mainly volatile fatty acids VFAs (formic, acetic, propionic, butyric, valerian, caproic), alcohols (methanol, ethanol), aldehydes, and gaseous products (carbon dioxide and hydrogen). The key factor impact on the products obtained in the phase is the hydrogen partial pressure formed during the process. At high pressure of the gas, less reduced metabolites such as lactate, butyrate, fatty acids with at least 3 carbon atoms in the chain (C3) are produced. On the other hand, under stable operating conditions (depends on the feedstock and species of bacteria), acetates, carbon dioxide, and hydrogen are produced, which are precursors for the production of methane in the fourth stage of AD (Anukam et al., 2019; Deublein & Steinhauser, 2011). This phase is characterized by a low pH (5-6) and an intense odor. In a balanced system, most of the organic matter is converted into readily available products for methanogens (acetate, hydrogen, and carbon dioxide), while the remainder (about 30%) is broken down into volatile fatty acids (VFAs) or alcohols (Anukam et al., 2019; Issah et al., 2020).

Phase III – acetogenesis - in which, organic acids and some aromatic compounds (e.g., benzoate) are converted into acetic acid, hydrogen, and carbon dioxide (Table S3, supplementary material). For thermodynamic reasons ($\Delta G0 < 0$), the necessary condition for the decomposition of the compounds is keeping the concentration of hydrogen formed during the process at a low level (Figure S3) (Anukam et al., 2019; Deublein & Steinhauser, 2011; Khanal, 2011).

In a properly functioning system, the partial pressure of hydrogen should be in the range from 10^{-4} Ba (a necessary condition for the reduction of carbon dioxide) to 10^{-6} Ba (oxidation of propionic acid) (Jędrczak, 2007; Ramirez et al., 2009).Therefore, acetogens exist in close symbiosis with other bacterial species between which the so-called interspecies hydrogen transfer (IHR) takes place, (Deublein & Steinhauser, 2011; Figure S.4. supplementary material). The generated hydrogen can not only be utilized by methanogens so-called hydrogenotrophs (Equation 12), but also by sulfate-reducing bacteria (SRB) e.g., *Desulfovibrio desulfuricans* (Equation 13). It is worth emphasizing the fact that sometimes there can be competition for hydrogen between the mentioned groups of microorganisms. In digesters, hydrogen can also be consumed by homoacetogenic bacteria such as *Acetobacterium woodii* and *Clostridium thermoaceticum* (Equation 14) (Anukam et al., 2019; Deublein & Steinhauser, 2011; Gallert & Winter, 2005; Khanal, 2011).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \ \Delta G^0 = -136\mathrm{kJ/mol} \tag{12}$$

$$SO_4{}^{2-} + 4H_2 \rightarrow S^{2-} + 4H_2O \ \Delta G^0 = -151\mathrm{kJ/mol} \tag{13}$$

$$2CO_2 + 4H_2 \rightarrow CH_3COO^- + H^+ + 2H_2O \ \Delta G^0 = -0,9\mathrm{kJ/mol} \tag{14}$$

At high ammonia concentrations, synthetic acetate oxidation (SAO) can also occur in this phase (Ramirez et al., 2009). This is a two-step process and involves oxidation by SAOB (syntrophic acetate oxidizing bacteria) of acetates to hydrogen and carbon dioxide (Equation 15) and for thermodynamic reasons the conversion of the resulting products to methane by hydrogenotrophic methanogens (Buhlmann et al., 2019). As reported by Ramirez et al. (2009) the effect of altering

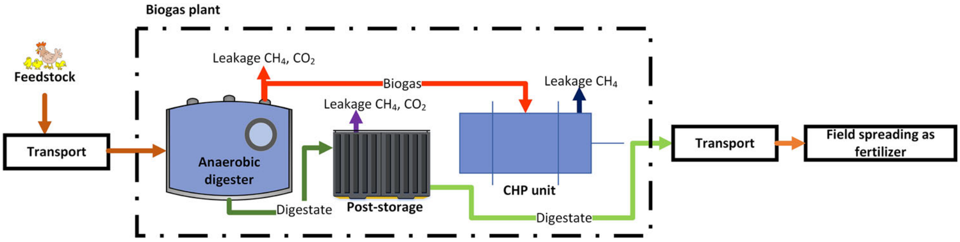

Figure 3. Flow chart of the anaerobic digestion of poultry manure, based on (Khoshnevisan et al., 2021).

the biochemical pathway of acetate degradation results in the reduction of biogas production.

$$CH_3COOH + 2H_2O \rightarrow 4H_2 + 2CO_2 \Delta G^0 = +104 kJ/mol \quad (15)$$

However, the enzymes involved in SAO require trace elements (especially cobalt, selenium, tungsten) for their proper function. Lack of supplementation of TE during AD can lead to SAO inhibition, and accumulation of VFAs in the fermentation broth. Molaey et al. (2018) indicated that supplementation of selenium during AD of PM has a critical role in the stable digestion performance and improves methane production at high organic loading rate and TAN levels.

Phase IV – methanogenesis – 70% of the methane is produced by the decomposition of acetic acid by heterotrophic bacteria (acetotrophic methanogens) (Equation 16). The remaining amount is generated by carbon dioxide reduction, of which only 5 to 6% is obtained from dissolved hydrogen. This phenomenon is explained by interspecies hydrogen transfer, during which hydrogen is not dissolved in the fermentation broth, but transferred directly from acetogens to methanogens (Deublein & Steinhauser, 2011; Jędrczak, 2007).

$$CH_3COOH \rightarrow CH_4 + CO_2 \Delta G^0 = -31 kJ/mol \quad (16)$$

Methanogens can also produce methane from the following substrates, (Frąc & Ziemiński, 2012): HCOOH, CH_3OH, CO, $(CH_3)_3N$, $(CH_3)_3NH$, $(CH_3)_3NH_2$, $(CH_3)_2S$, Me^0. Some methanogens can only convert one substrate e.g., *Methanobrevibacter arboriphilus* or *Methanosaeta* - H_2/CO_2 and acetate, respectively. While others are more versatile e.g., *Methanospirillum hungatei* and *Methanobacterium formicicum* and capable of taking up formate, or genus *Methanosarcina* can convert a wide range of compounds e.g., H_2/CO_2, acetate, methanol, methylamines, acetic acid, carbon monoxide (Sousa et al., 2007).

However, determining the environmental impact of AD and analyzing the carbon cycle during this process requires a broader view. Apart the biogas production, loses of methane during production and transmission, losses of gases during digestate storage as well as emission from cogeneration units should also be taken into account (Figure 3). Table S4 (supplementary material) summarizes the formulas that can be used to estimate gas emissions during the AD (Kreidenweis et al., 2021).

A separate issue is the fate of micropollutants and emerging contaminants during AD. The removal of antibiotics, antibiotic resistance genes (ARGs), and heavy metals under anaerobic conditions are debatable (Riaz et al., 2020). Zhang et al. (2019) demonstrated that microwave pretreatment of manure and activated carbon enhanced ARGs removal and methane production during mesophilic AD of PM. Enrofloxacin in dose 8 mg kg^{-1}·TS promoted the AD, while higher than 16 mg kg^{-1}·TS inhibited the biogas production rate (Du et al., 2022). However lack is explanation why most of these pollutants are still present in the digestate (Gurmessa et al., 2020). Riaz et al. (2020) and Gurmessa et al. (2020) suggested that following factors play important role in the degradation: i) the operational parameters of the AD (e.g. temperature, hydraulic retention time, etc.); ii) microbial community structure; iii) the physicochemical character of the substrate; iv) genetic elements. Despite that the digestate before application to the soil is treated (e.g., composting or solid-liquid separation (SLS) which reduce manure contaminants (Congilosi & Aga, 2021) still the attention must be put to optimization of post-treatment processes as well as aspects related to feedstock preparation (Gurmessa et al., 2020).

3.3. Biochar production and carbon sequestration potential

Pyrolysis temperature and biochar substrates have impact on the stability of C in biochar and determine its application (Tab.1).

Table 1 selected biochar properties described by (Novak et al., 2009, Song & Guo, 2012, Srinivasan et al., 2015, Khan et al., 2016, Qi et al., 2017, Li et al., 2018, Bavariani et al., 2019, Wystalska et al., 2021)

The C content (86.70%) in biochar from PM is significantly higher, than in other biochar types produced at similar temperatures, due to a high proportion of litter material in the substrate converted into biochar (Srinivasan et al., 2015). Presence of stable C cause that biochar can also be used to sequester carbon in the soil. Using pyrolysis, more than half of the C of biomass can be converted into permanent C-sinks instead of lost as CO_2 (European Biochar Certficate 2020a) (Figure 4). Application of biochar to soil or feed additives average degradation rate is about 0.3% per year. This means that 100 years after biochar application to soil, biochar would still sequester about 74% of the original carbon (European Biochar Certficate 2020a). Moreover, the use of biochar on cultivated soils reduced CH_4 emissions and improved the soil ability to absorb greenhouse gases. The use of biochar from chicken manure for maize cultivation caused reduction in CO_2 of 3.2 kg per 1 kg of biochar (Panwar et al., 2019)

Biochar with a high aromatic carbon content is probably suitable for long-term sequestration of C (Novak et al., 2009). The stability of biochar depends on the O/C molar ratio, the lower its value, the potentially longer the half-life period of biochar and the higher its usefulness for

Table 1. Selected biochar properties described by (Novak et al., 2009, Song & Guo, 2012, Srinivasan et al., 2015, Khan et al., 2016, Qi et al., 2017, Li et al., 2018, Bavariani et al., 2019, Wystalska et al., 2021).

Substrate	Temperature	pH	ash	C	H	N	S	P	K	Ca	CEC	BET
	°C	–			%						cmol kg^{-1}	m^2 g^{-1}
Poultry litter/ poultry manure	200-700	7.2-12.8	11.16-60.78	32.30-86.70	0.3-5.62	0.12-4.90	0.4-3.53	2.27-6.38	1.04-9.15	7.17-9.40	29.2-86.5	1.1-86.7

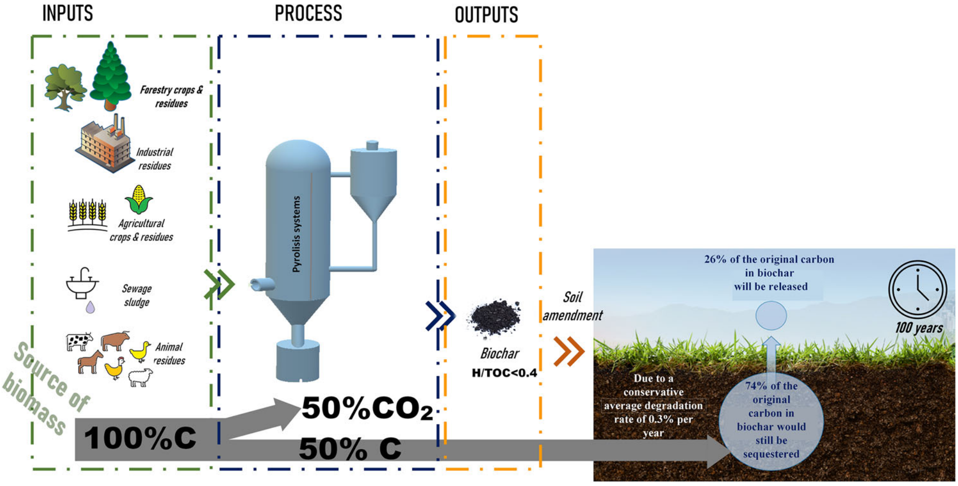

Figure 4. Scheme of transformation of C contained in biomass into C-sinks, based on (European Biochar Certficate 2020a).

sequestration of C in soil. The O/C ratio of biochar studied by Srinivasan et al. (2015) was low and equal to 0.12, similarly in the study reported by Novak et al. (2009), the O/C ratio was 0.14 and < 0.01. Higher O/C in biochar, i.e. 0.46 and 0.48 was reported by Li et al. (2018). The O/C > 0.6 indicates the half-life of the biochar $<$100 years. A range of O/C values of 0.2-0.6 may indicate a half-life of 1000-100 years(Srinivasan et al., 2015, Zhang et al., 2017). The O/C < 0.2 extends the half-life $>$ 1000 years. In turn, high values of H/C ratio suggest that biochar will degrade quicker in the soil which will result in an increased emission of CO_2 (Van Zwieten et al., 2010). The greatest potential for sequestration of C is displayed by biochar with the H/Corg below 0.4 (Brassard et al., 2018) and may achieve the value H/C ratio of 0.013 (Srinivasan et al., 2015). The low H/C ratio, indicating the high aromaticity of the analyzed biochar, affects the potential of C sequestration. Among biochar produced from different substrates at 680°C, only biochar from pine sawdust had a higher potential to longer storage in the soil than poultry manure biochar.

For the assessment of C sequestration potential, the overall carbon balance should include all direct and indirect emissions from e.g., biomass production (planting, cultivation, harvesting, transport, crushing), the processing of biomass into biochar and its final treatment (e.g. grinding, mixing, packaging), transport, and soil application (European Biochar Certificate, 2020b), (Figure 4).

CO_2 equivalent (CO_2eq) covers all GHGs in effect of production and treatment of the biomass, its conversion in a pyrolytic installation, and the processing of biochar (European Biochar Certificate, 2020a). The calculation example for the C-sink potential based on guidelines of EBC (i.e. European Biochar Certificate, 2020b) is shown in Table S5 (supplementary material). If renewable energy is used in the production of biochar, CO_2eq is considered to be zero and similarly when electricity corresponding to at least its consumption is generated in the production of biochar in the pyrolysis process (European Biochar Certificate, 2020b). Only biochar produced from C-neutral biomass, e.g., biomass that is waste or by-product that meets certain requirements (European Biochar Certificate, 2020b), is eligible for C-sink certification.

4. Nitrogen cycle

4.1. Forms of nitrogen in poultry manure

High nitrogen content (3-5% PM dry weight) in the form of uric acid (40-70%), feed protein (10-40%), urea (4-12%) and ammonium (4-20%) (Bhatnagar et al., 2022) depends primarily on animal diet, type and age (Nahm, 2003) when applied to soil undergoes a number of transformations (Figure 5). During PM storage organic N is converted into ammonia which leads to volatilization and N loss into the air. When poultry manure is applied to soil for plant uptake N from organic forms is converted through mineralization to N mineral forms. This depends mainly on pH, temperature and moisture content.

4.2. Ammonia emission

Effect of poultry production is gaseous emissions of carbon dioxide, ammonia, hydrogen sulfide, methane, nitrogen oxides, dust and others. Ammonia emission from poultry manure is higher than from cattle and cow manure and during the three-month storage period was 2.94 kg Mg^{-1}, pig manure 2.40 kg Mg^{-1} and cow's 0.45 kg Mg^{-1}, respectively. It also depends on the type of poultry, feed and a breeding system. The highest amount of ammonia is obtained from turkey manure - over 950 kg/year per 1000 birds, from ducks at 680 kg/year from 1000 heads goose at 350 kg/year per 1000 birds whereas smallest broiler chickens generated about 220 kg ammonia/year per 1000 birds. Stable ventilation of farm buildings, can reduce the amount of ammonia by

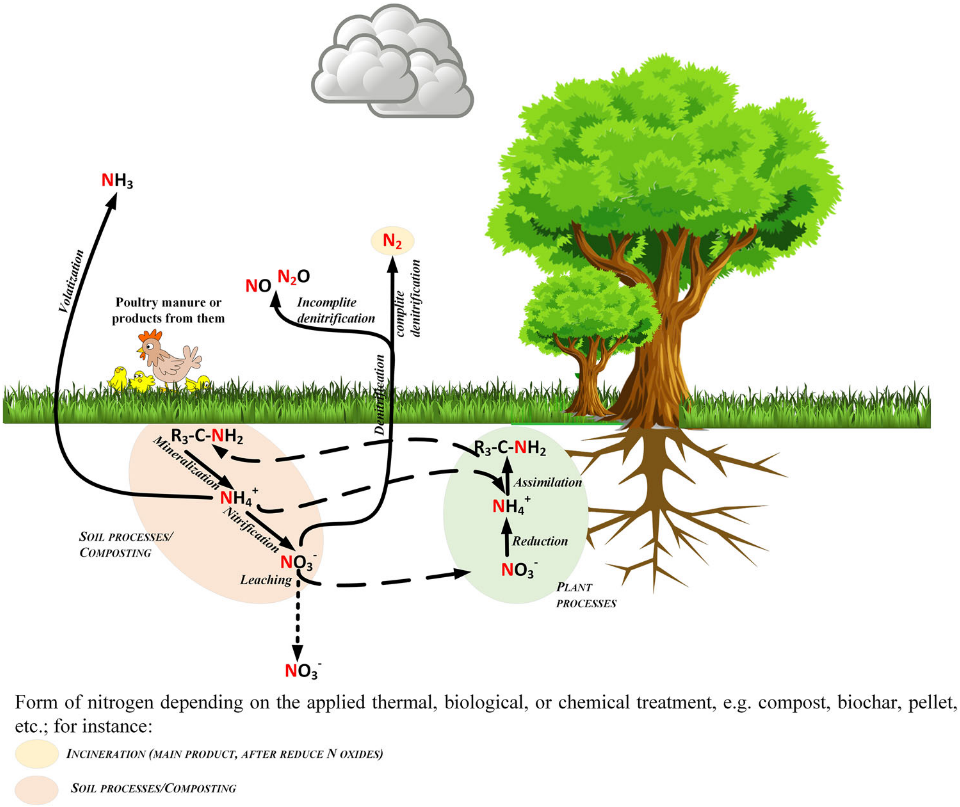

Figure 5. Transformation of nitrogen based on poultry manure in soil based on (Ros et al., 2020).

about 20% by decrease the interior temperature, thus slowing down the uncontrolled processes of organic matter decomposition (Bittman et al., 2014). The decrease of ammonia generation is also achieved by acidification of the liquid part of the manure, e.g. with sulfuric acid to a pH of 3.5-5.5.

During composting too fast or absent thermophilic phase and an unfavorable C:N ratio (range 40-50: 1) results in the formation of slow-acting organic combinations of nutrients. During this time, the mesophilic microflora develops excessively, which allows for the maintenance of the chemical activity of urease causing excessive ammonia emissions (Krawczyk & Walczak, 2016).

Ammonium ion (NH_4^+) and/or free ammonia nitrogen (FAN) are the main inorganic products of decomposition of organic nitrogen fraction in phase II – acidogenesis of anaerobic digestion (AD). The equilibrium state is established between the forms mentioned above of nitrogen, and their share in total ammonia nitrogen (TAN – sum FAN and NH_4^+) depends on the pH. As the pH increases, free ammonia nitrogen (FAN) increases. At neutral pH, the dissociated form prevails; only 0.5% of nitrogen is in the form of free ammonia, while at pH equal to 8, its (FAN) share increases to 5% (Deublein & Steinhauser, 2011). Accumulation of TAN in the digester can lead to inhibition of the process. The inhibition mechanism caused by ammonia can be related to: i) inhibition of specific enzymatic reactions (blocking enzymes); ii) pH imbalance inside the cell and thus the disturbance of the acid-base balance and/or potassium deficiency; iii) the accumulation of VFAs (there is an interaction between FA, pH and VFAs; disturbance of the process balance leads to accumulation of VFAs in the chamber, resulting in a decrease in pH and thus decrease FAN concentration). Moreover, ammonia inhibits the process of acetic acid uptake (Jiang et al., 2019, Fuchs et al., 2018). It is difficult to indicate the TAN limit value for inhibition of the AD of PM because it depends on the characteristics of feedstock, inoculum characteristics, process conditions (temperature, pH), form of nitrogen (FAN is more toxic than ammonium ions, process inhibition for FAN is observed at concentrations higher than 45-100 mg $l^{-1}$and for ammonium ions higher than 1700 mg l^{-1}) and a degree of adaptation of bacteria to TAN (generally, a gradual increase of ammonia concentration promotes adaptation to it). For this reason, a wide range of inhibiting TAN concentrations has been reported in the literature (from 1.7 g $l^{-1}$to 14 g l^{-1}) (Duan et al., 2018; Reyes et al., 2021; Yin et al., 2021) However, it is important to note that adaptation of microorganisms to high ammonia concentrations can result in high ammonia concentrations in the digestate. According to Ortakci et al. (2019) the concentration of ammonia nitrogen in such a digestate can be higher than 5000 mg dm^{-1}.

4.3. Nitrous oxide and nitric oxide emission

Nitrous oxide (N_2O) and nitric oxide (NO) can be emitted as a result of nitrification where NH_4^+ is a substrate for aerobic respiration or alternatively – denitrification when oxygen is limited and NO_3^- is used for anaerobic respiration as an electron acceptor by microorganisms.

N_2O has a global warming potential of 298 times that of CO_2 (IPCC, 2019) and can be the main GHG contributor (Ziganshina et al., 2015; Zhu et al., 2020). Meta-analysis results showed that PM considerably increased CO_2, CH_4, and N_2O emissions than pig and cattle manure (Shakoor et al., 2021). Soil application of PM during autumn season resulted in N_2O emission at the level of 1.52% total N applied (Thorman et al., 2020). Indirect N_2O emissions may arise from the re-deposition of volatilized NH_3 and NO_x onto nearby soil, providing a substrate for nitrification and denitrification. The important factor is C:N value (Charles et al., 2017). Nitrogen are lost to surface water via leaching of NO_3^- which is later denitrified (Thorman et al., 2020).

Moreover, many other factors influenced emission, such as soil properties (texture, drainage, bulk density, water holding capacity), SOC, $N_{tot.}$, crop rotation, duration of the land management and climatic factors. Soil nitrogen cycle is closely related to soil C cycle and therefore increased SOC sequestration might even cause increase N_2O emission. The process can be mitigate by biochar or non-pyrogenic C amendment application (Janczak et al., 2017, Guenet et al., 2021).

4.4. Leaching and runoff lost

Nitrogen losses from livestock production through leaching and runoff loss can reach up to about 50%. Nitrogen losses through leaching occur mostly in the form of nitrates (NO_3^-) which is favored by high soil moisture, heavy rainfall, excessive irrigation, and poorly developed root systems of plants. Uncontrolled losses of NO_3 to groundwater can be harmful to human health in dose higher than 50 mg l^{-1} NO_3. Light soils, i.e. fawn, podzolic, and rusty podzolic soils, created on the basis of sands, are very permeable, airy, and quickly heat up, contributing to the rapid leaching of nitrates and their seepage into the soil profile and further into the groundwater. On the other hand, heavy soils, i.e. mainly clays and loams, poorly permeate water and oxygen to the deeper parts of the soil profile. They limit the leaching of nitrates, but plants growing on such soils have a problem with the properly growth through a too compact structure. A soil with a sand and clay fraction is optimal, which makes it good for plant growth and does not allow significant amounts of nitrogenous compounds to pass into groundwater (Soroko & Strzelczyk, 2009).

5. Phosphorus cycle

5.1. Forms of phosphorus in poultry manure

The content of phosphorus in PM is 2 to 4 times higher than in other manure and ranges from13.6 to 25.4 g P_2O_5 kg^{-1}dm (Table S.6, supplementary material). Because in cereals and others (barley, wheat bran, soybean, rapeseed meal), phosphorous occurs in form of inaviable phytin, hence, the phytic form is present in significant amounts in poultry excreta (Toth et al., 2011, Ashworth et al., 2020). Available phosphorus sources for birds are mineral supplements added to feed (Sharpley et al., 2007). The inorganic phosphorus in PM is in the range of 32-84% wt (Othake & Tsuneda, 2019) and organic in the range of 14-68% wt, with the potential to be mineralized to a plant-available form (He et al., 2008). Pagliari and Laboski (2014) found that the solid phase of phosphorus is not entirely organic, but is combination of minerals and organic compounds. The inorganic phosphate fraction includes calcium phosphate, dibasic calcium phosphate, and poorly bound water-soluble phosphorus (He et al., 2016). Both fractions of total phosphorus (orthophosphates and organic phosphorus) are essentially immediately labile. Phytates are an exception. Compared to other animal manures, poultry manure contains proportionally more of the stable form of phosphorus, which ranges from 22 to 58% of total phosphorus (Dail et al., 2007).

Between 12 and 20% of the phosphorus in PM is in a water-soluble form and is washed away in rainfalls after being applied to the soil (Guo et al., 2009). Combustion of poultry manure to produce nutrient-rich ash for agricultural applications is the most environmentally friendly methods (Fahimi et al., 2020; Kaikake et al., 2009). The phosphorus content in ash ranges from 8.3 to 13% and is comparable to that of some natural phosphate rocks (Desmidt et al., 2015). The amorphous phase of phosphorus in poultry ash is a source of a bioavailable form of phosphorus, and depends on the combustion temperature (Vance, 2019). The main mineral phase of the ash is potassium-sodium-calcium phosphate $(K,Na)Ca_2(PO_4)_2$ and in the form of calcium phosphates (hydroxyapatite and whitlockite) - from 8.8 to 14.8% P_2O_5. Bioavailable forms in ash may achieve to 31% d.w.P_2O_5 of total content (Table S7, supplementary materials) Song and Guo (2012) demonstrated that the conversion of poultry manure to biochar by slow pyrolysis at $\geq$ 350 °C reduced the proportion of water-soluble phosphorus from 19.5% to less than 6.9%. This will help maintain a steady and long-term supply of nutrients in the soil preventing rapid nutrient loss during runoff. Such an effect can be achieved by converting poultry manure by pyrolysis into biochar and its use as a soil additive (Guo et al., 2020; Haider et al., 2021). Wang et al. (2015) found that pyrolysis immobilized the water-extractable phosphorus contained in raw PM by converting it into more stable, less available minerals (Mg and Ca phosphates) present in biochar (Figure S6, supplementary materials). Phosphorus content in biochar from PM was higher than that of unprocessed manure and increased with pyrolysis temperature from 3.391% in 200 °C to 6.38% in 500 °C (Table S8, supplementary material), Bavariani et al. (2019).

Experiments on sequential leaching of biocarbon from raw poultry manure produced at 600 °C showed that phosphorus was released slowly but in much higher (43.2 mg g^{-1}) amounts compared to other biochars of animal and lignocellulose origin (Table S9, supplementary material), (Hadroug et al., 2021). The total amount of released phosphorus was about 95% of its original content in the biochar.

Negassa and Leinweber (2009) evaluated the balance of nutrients (including phosphorus) in poultry litter used as a fertilizer for five different treatments: direct application on the ground; composting; composting and pelleting; co-digestion with feed corn; thermal conversion. Final products of all the treatment methods contained the same amount of phosphorus (in the form of P_2O_5) per Mg of processed litter. In the case of ash, the annual efficiency of P_2O_5, depending on the crop, varies from 37% to even 100%. In contrast, it is around 70% for other products. The effectiveness of P_2O_5, depends on the crop and soil type where poultry litter ash is used as a fertilizer. Figure S5 (Nusselder et al., 2020, supplementary materials) shows the fertilizer equivalents available in the first year to plants, delivered from 1 Mg of poultry litter, treated using various methods.

5.2. Poultry manure struvite

Struvite ($MgNH_4PO_4{\cdot}6H_2O$), i.e. hydrated ammonium-magnesium phosphate can be an alternative source of phosphorus contain the two macronutrients (phosphorus and nitrogen) needed for plant growth and development. Struvite is formed by the following reaction (17):

$$Mg + NH_4{}^{+} + PO_4{}^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O \downarrow \tag{17}$$

According to low solubility (Rech et al., 2018) the fertilizing components are released slowly and the plants themselves stimulate the intensity of release which reduces the need for frequent fertilization. No leaching is observed, either into surface water or to deeper soil layers where phosphorus could become unavailable to plants. Struvite is as effective as compound fertilizer, providing plants with the right doses of nutrients N, P, K, Ca, and Mg (Krishnamoorthy et al., 2021; Zhang et al., 2020).

Struvite produced from the acidified PM ash extract after supplementing with Mg and adjusting the pH to about 8.5 contained 90% of the phosphorus originally present in fresh chicken manure (Poblete-Grant et al., 2020). The process yielded a multi-nutrient fertilizer composed of struvite-$NH_4{}^{+}$, struvite - K, and significant amounts of potassium sulfate and hydroxyapatite, with a high content of macroelements (P, K, Mg, S), low content of microelements, and lower levels of heavy metals compared to fresh manure (Poblete-Grant et al., 2020).

Poultry manure is a good source of phosphorus for the production of universal agricultural fertilizer (Rivera et al., 2022; Sarvi et al., 2021). Yilmazel and Demirer (2013) confirmed the recovery of nutrients (N, P) by precipitation of struvite from poultry manure using HCl. However, it further led to the dissolution of metals along with nutrients and crystallization of other minerals along with struvite. It was also found that high concentrations of Ca^{2+} ions allow complete recovery of phosphorus from a solution due to calcium phosphate precipitation.

5.3. The mobility of phosphorous in environment

The biogeochemical cycle of phosphorus is very sensitive to agricultural and industrial activity, especially to poorly planned or implemented agrotechnical procedures that modify the natural P cycle (Figure 6).

The content of total phosphorus in soil ranges from 100 to 3000 mg P kg^{-1} (Sönmez et al., 2016), but is mostly in the range of 500-800 mg P kg^{-1} soil and depends on the type of bedrock, the degree of weathering, and the content of organic matter. This amount exceeds many times the average nutritional needs of plants. However, only 0.03-0.5 mg P kg^{-1} is actually available to plants, as most of the phosphorus binds in the soil with various chemical forms of other elements (e.g. 2- and 3-valent metal cations, i.e. Mg, Ca, Fe and Al), forming hardly soluble compounds. Phosphorus content decreases with the depth of the soil profile. The active phosphorus in the soil solution is phosphorus in the form of phosphate ions ($H_2PO_4{}^{-}$, $HPO_4{}^{2-}$), taken up directly by plant roots. When the amount of active phosphorus decreases due to intensive plant uptake, mobile phosphorus is converted to its bioavailable form, making up for the deficiency. Another form of phosphorus is reserve phosphorus in the form of hard to dissolve minerals, i.e. apatite, phosphate rock and variscite (Mulgueen et al., 2004). Therefore, the phosphorus cycle in the soil is influenced by its biological activity and high enzyme production/activity associated with organic phosphorus hydrolysis. The following extracellular phosphatases are mainly involved in phosphorus metabolism in the soil: acid phosphomonoesterase, alkaline phosphomonoesterase, and phosphodiesterases, (Waldrip et al., 2011). Manure application increases the concentration of total and soluble phosphorus in the soil and the concentration of stable organic groups of this element (Waldrip-Dail et al., 2009).

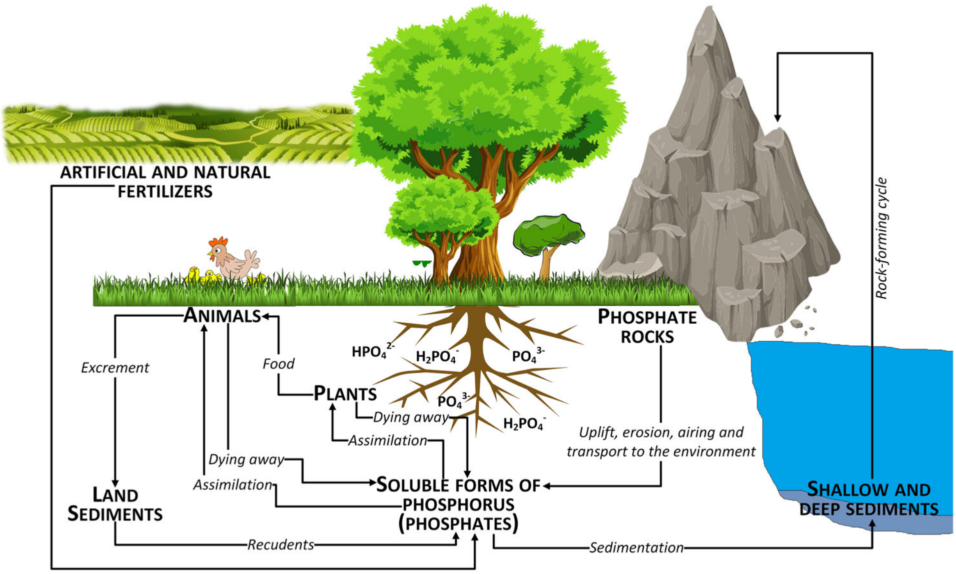

Figure 6. The cycle of phosphorus in environment based on own study.

Depending on the form of occurrence (type of binding) and variation of soil and water conditions (i.e. soil reaction, the organic matter, Fe and Al), phosphorus may be released to soil solution and ground water and as a consequence, through leaching, move deep into the soil profile or undergo the process of leaching to surface waters (McDowell et al., 2011). The following mechanisms are responsible for phosphorus transfer from soil to water: i) chemical dissolving; ii) physical separation and removal of soil particles through erosion; iii) incidental migration from soil to water after application of phosphorus fertilizer or manure in conditions that are not conducive to its permeating into the soil structure, (Roy, 2017).

The release of phosphorus from the soil in the presence of organic carbon, is associated with leaching of its soluble forms into groundwater which with high mineralization efficiency and low phosphorus utilization by plants results in contamination of groundwater (Figure S7, supplementary material). Phosphorus bound to mineral and organic soil particles accounts for 60 to 90% of phosphorus transported through surface runoff. Dissolved forms include phosphorus desorbed from the soil, leached from plant residues, and released from sources such as mineral fertilizers and manure. In catchments in agricultural areas, the level of phosphorus leaching may be about 0.5 kg ha^{-1}. The process of phosphorus leaching is a type of the flow through privileged pathways of underground flow, i.e. the networks of regular cracks and macropores, huge cracks in the soil, chasms and channels carved by the soil fauna, root channels and wedges, lenses and layers that are characterized by improved filtration parameters than other parts of the soil. These migration pathways are responsible for the intensity and time of solution transfer (including phosphorus) during precipitation and thawing (Weiler & McDonnell, 2007).

Excessive or inappropriate application of manure and litter can result in increased accumulation of phosphorus in the soil and subsequent increase in surface runoff, leading to eutrophication of reservoirs, (Tiessen et al., 2011). Transport of phosphorus contained in PM after its application in the soil shown that dry mass of the manure decreased over time, but the concentrations of phosphorus in the manure were essentially constant over time, meaning that it was removed from the manure at the same rate as it decomposed Vadas et al. (2007). Numerous studies have also examined the effects of drying conditions on phosphorus content in PM (He et al., 2006). For broiler manure, freeze-drying or oven-drying (105 °C) yielded lower concentrations of inorganic and total phosphorus than for air drying (Akinremi et al., 2003). The drying process can cause the relatively stable phosphorus in PM to shift to more labile, or conversely, insoluble forms (Dail et al., 2007). Crops are unable to absorb the high doses of phosphorus contained in PM, so the excess accumulates in the soil. The P availability for plants can be increased by mixing with calcium-rich opoka rock (Kacprzak & Sobik-Szołtysek, 2022). Other possibility is adding sulfur-phosphate mixtures. This results in the oxidation of sulfur to sulfuric acid through the activity of *Thiobacillus spp*. bacteria. The reaction with acid led to the partial decomposition of phosphates and the formation of mono- and dicalcium phosphates, which are more readily available to plants (Figure S7, supplementary material).

6. Conclusion

Poultry manure is historically used as a fertilizer, however positive impact of application on the increase of the plant yield or the improvement of soil properties depends on many factors, such dose, soil type or temperature. Generally, increase of organic matter content, nitrogen ammonification, pH value, content of P, K, Cu, Mn, Fe and Zn available to plants is noted. However, PM can affect enzyme activity and introduce contaminations (e.g. pathogens; antibiotics, heavy metals). Moreover, ammonia, NO_x emission or unbalanced C:N ratio in soil poses serious environmental problem.

Technological processes of PM has both positive and negative effect on carbon, nitrogen and phosphorous transformations and gases emissions. During aerobic processes (composting) nitrogen is lost by leachate of NH_4^+, NO^{3-} or by emissions of NH_3, N_2O, $N_{2;}$ carbon by emissions of CO_2, CH_4 and phosphorus by the leachate in the form of $HPO_4^{2-,}$ H_2PO_4, respectively. In turn, the main challenge of anaerobic digestion is optimization toward high methane production. PM is not an easily biodegradable substrate, hence modification of technological parameters and co-substrates additives is required to increase the process efficiency and to obtain a digestate can be used as valuable fertilizer. Finally, thermal treatment requires energy for PM drying and monitoring of specific emissions. However from other hand products resulting from thermal processes have great potential for carbon (biochar) and phosphorous (ash) long-storage.

Regardless of the technology used, PM can be a suitable substrate for the production of valuable products that have a positive impact on the environment.

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