Journal of Environmental Management 264 (2020) 110327

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

Management of poultry manure in Poland – Current state and future perspectives

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ARTICLE INFO

Keywords:
Poultry manure
Management
Nutrient and energy recovery
Circular economy
Agriculture

ABSTRACT

This review aimed to analyse the current state of management practices for poultry manure in Poland and present future perspectives in terms of technologies allowing closing the loops for circular economy, and thus recovery of nutrients and energy. The scope of the review focused primarily on: (1) the analysis of poultry production and generation of poultry manure with special references to quantities, properties (e.g. fertilizing properties), seasonality, etc.; (2) the overview of current practices and methods for managing poultry manure including advantages and limitations; (3) the analysis of potential and realistic threats and risk related to managing poultry manure, and also (4) the analysis of promising technologies for converting poultry manure into added value products and energy. The review addressed the following technologies: composting of poultry manure to obtain fertilizers and soil improvers, anaerobic digestion of poultry manure for energy recovery, and also pyrolysis of poultry manure into different types of biochar that can be applied in agriculture, horticulture and industry. Poultry manure is rich in macro- and micronutrients but also can contain various contaminants such as antibiotics or pesticides, and thus posing a realistic threat to soil and living organisms when applied to soil directly or after biological treatment. The main challenge in poultry manure processing is to assure sufficient closing of carbon, nitrogen and phosphorous loops and safe application to soil.

1. Introduction

Poland is one of the major leaders in poultry production in Europe. Production of poultry is estimated on average at 4 mln ton per year – this included broiler chickens and turkeys, and egg-laying hens (Tańczuk et al., 2019a,b; Tańczuk et al., 2019b). The number of poultry farms in Poland has been gradually increasing since a decade. This in turn, has resulted in even higher quantities of poultry manure that need to be properly managed, either on site through available technologies or in more centralized approach e.g. in composting facilities, biogas plants or other.

Poultry manure is rich in nitrogen but also contains significant quantities of phosphorous and potassium. Due to the composition and the content of selected nutrients poultry manure can be applied as a fertilizer to improve soil properties and fertility. However, with increasing quantities of poultry manure in Poland there is no sufficient agricultural land for application of poultry manure. Excessive quantities of poultry manure require transportation, storage and further handling and/or processing. Uncontrolled management of poultry manure can cause emission of methane, carbon dioxide and ammonia into the atmosphere. What is more, poultry manure applied to soil in excess and in uncontrolled manner can pose a serious threat to soil and water environment.

Therefore, managing poultry manure requires a complex approach. There is a number of available technologies that would allow recovery of nutrients and energy from poultry manure on site using the infrastructure of poultry farms. However, some of those already commercially available technologies would require the adjustments of farm infrastructure and substantial capital investment. Complex approach to efficient management of poultry manure would require overcoming a number of obstacles that include handling and transportation, changes in the type and composition of poultry manure due to seasonality and breeding regime, demand for products obtained from poultry manure such as fertilizers and soil improvers, and also technological, e.g. high

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https://doi.org/10.1016/j.jenvman.2020.110327
Received 8 December 2019; Received in revised form 13 February 2020; Accepted 22 February 2020
Available online 26 March 2020

moisture content and structure of poultry manure, technological operations, e.g. pre-treatments and post-treatments, etc. There are many ongoing research projects in Polish research and academic institutions aiming at developing novel and more efficient technologies for converting poultry manure into energy or added value products. The research has been driven by the concept of a poultry biorefinery – an approach to manage and process poultry manure on site for energy and nutrient recovery and production of added value products. However, this concept has not been fully explored in terms of its potential, implementation, policies and support. There is little known about operating manure biorefineries in literature (Awasthi et al., 2019).

The rationale behind this work – which is the part of the H2020 project "Transition towards a more carbon and nutrient efficient agriculture in Europe" (2018–2022) – is that first and foremost, there is a necessity to manage and process poultry manure in more efficient and safe manner allowing to close carbon, nitrogen and phosphorus loops in agriculture. The novelty of this work lies primarily in the revision of limitations to selected technologies and methods for handling and processing poultry manure. Also, this work presents the analysis of the potential and realistic risks and threats related to poultry manure, particularly when directly or after biological treatment applied to soil.

The overall goal of this review was to analyse the current state of management practices for poultry manure in Poland and present future perspectives in terms of technologies allowing closing the nutrient loops for a circular economy and recover nutrients and energy. The scope of the review included: (1) analysis of poultry production and generation of poultry manure with special references to quantities, properties (e.g. fertilizing properties), seasonality, etc., (2) legal framework and policies for management of poultry manure, (3) potential and realistic threats related to applications of poultry manure, (4) overview of current practices and methods for managing poultry manure including advantages and limitations, (5) analysis of promising technologies for converting poultry manure into added value products and energy.

2. Case study of Poland

According to the EUROSTAT data production of poultry in the EU-28 in 2018 was as follows: Poland – 16.8%, UK – 12.9%, France – 11.4%, Spain – 10.7%, Germany – 10.4%, Italy – 8.5%, Hungary – 3.5% and the remaining constituted in total – 26.0%. Over the years Poland has been a leader in poultry production in Europe and according to the recent statistics the production is on the increase (Fig. 1).

In 2017, the total amount of poultry production was estimated at 192.1 mln birds – the amount of chickens was estimated at 176.7 mln (including 53 mln laying hens) (Statistics Poland, 2019). In the first quarter of 2018 the amount of 619.92 thousand tons of poultry meat was produced. It is about 20 thousand tons more than currently of the year in 2017 (Eurostat, 2018). This makes Poland a particularly interesting case

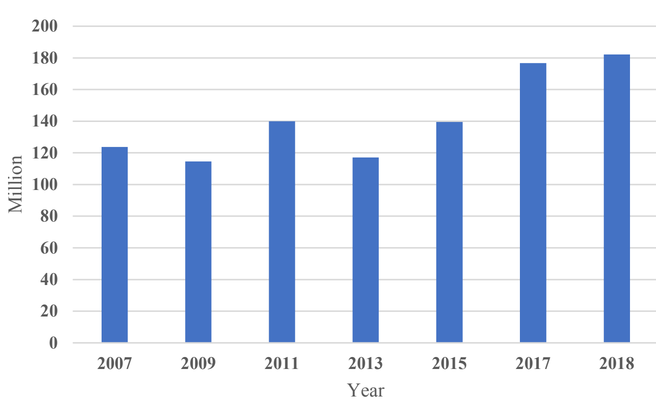

Fig. 1. The number of chickens and lying hens in 2007–2018 (Statistics Poland, 2019).

study in terms of dynamic poultry production and consumption, increasing generation and efficient management of poultry manure.

2.1. Poultry production

The poultry market in Poland is divided into two segments, i.e. gallinaceous birds (hens and turkeys) and water birds (geese and ducks). There are two main directions of poultry production, i.e. for eggs and meat. Poultry meat is produced from chicken, duck, turkey and geese broilers. Hens and turkeys are produced in intensive breeding, other poultry species are produced in extensive and semi-intensive breeding systems.

In Poland 86.8% of poultry is raised in cage breeding system, 9.6% in bedding system, 3.2% in free range system and only 0.3% in organic system. As for the European Union, the cage breeding system also predominates (58.7%), whereas more poultry is raised in bedding system (27.5%) and free-range system (9.2%), and organic system (4.6%) (National Chamber of Poultry Producers and Feed, 2019).

Poultry farms of different size, structure and breeding systems are located all over the country and include free range farms (less than 350 birds), non industrial scale farms (from 350 to 10 thousand birds), small industrial-scale farms (from 10 thousand to 15 thousand birds), medium industrial-scale farms (from 15 thousand to 52.5 thousand birds) and large industrial-scale farms (52.5 thousand birds and more). According to statistical data for laying hens, it is estimated that there are about 580 non industrial-scale farms, 84 small industrial-scale farms, 311 medium industrial-scale farms and 157 large industrial-scale farms in Poland (General Veterinary Inspectorate, 2019). Fig. 2 presents the distribution of poultry farms in Poland in 2018 (General Veterinary Inspectorate, 2019).

2.2. Generation of poultry manure

It is estimated that the total amount of manure produced annually is 4,494,639 Mg from all types of poultry farming in Poland, 2017 (Tańczuk et al., 2019a,b; Tańczuk et al., 2019b). Consequently, in view to the distribution of poultry farms in different voivodships in Poland, the highest quantities of poultry manure were reported for Mazowieckie and Wielkopolskie voivodships. According to the most recent data from 2018 the quantities of poultry manure generated in different systems, i. e. cage breeding, bedding system (also referred to as litter breeding system) and free-range system are presented in Fig. 3.

It is reported that the annual generation of manure from the cage breeding system in Poland is at 1,830,908 Mg. Most of the manure is generated in such voivodships as Wielkopolskie (673,472 Mg/a), Mazowieckie (379,381 Mg/a) and Małopolskie (84,596 Mg/a). As for the litter breeding system, the annual production of manure is estimated at 272,570 Mg/a. The highest quantities are generated in Mazowieckie (38,905 Mg/a), Podlaskie (31,868 Mg/a) and Śląskie (31,633 Mg/a) voivodships. The annual generation of manure from the free-range breeding system is estimated at 61,538 Mg/a with the highest quantities in Mazowieckie (514,872 Mg/a), Wielkopolskie (324,019 Mg/a) and Podlaskie (212,007 Mg/a) voivodships.

2.3. Legal framework for managing poultry manure

Management of poultry manure has to fulfil the requirements of the Regulation of the European Parliament and the Council (CE) No 1069/2009 of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation) and the Regulation of the European Parliament of the Council (CE) No 142/2011 of 25 February 2011 implementing Regulation No 1069/2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and implementing Council Directive 97/78/EC as regards certain

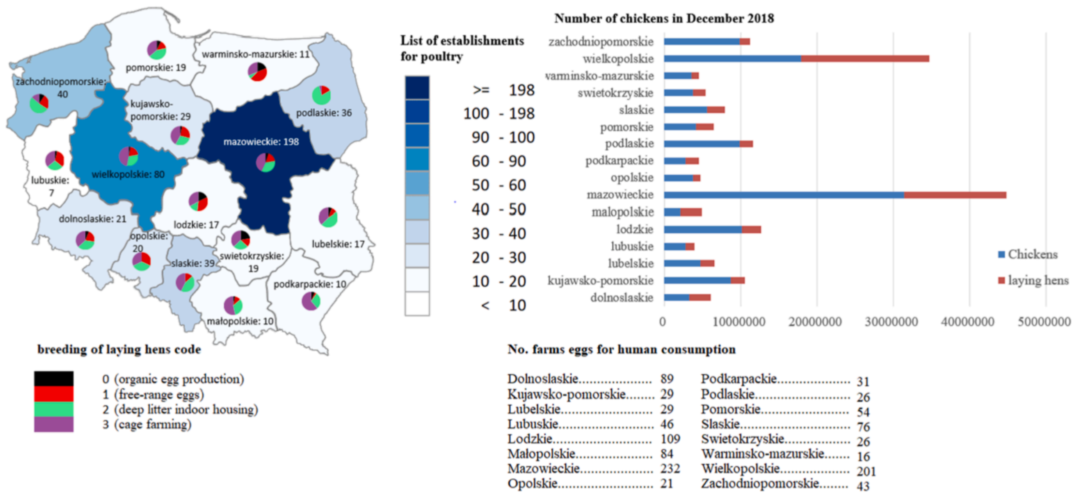

Fig. 2. The number of poultry farms in the voivodships in Poland (Based on data from General Veterinary Inspectorate, 2018).

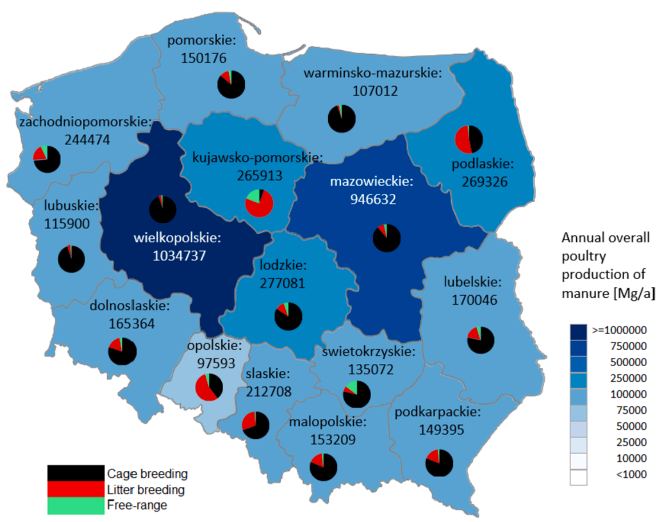

Fig. 3. Production of poultry manure in Poland in 2018 (Tańczuk et al., 2019a, b; Tańczuk et al., 2019b).

samples and items exempt from veterinary checks at the border under that Directive (Regulation of the European Parliament and Council (CE) No 1069/2009; Regulation of the European Parliament and Council (CE) No 142/2011).

These legal documents lay down the rules for handling and managing poultry manure defined as any excrements and/or urine of farmed animals other than farmed fish, with our without litter. Poultry manure is classified into the category 2 of animal by-products and could be:

- used to produce organic fertilizers or soil improvements and placing onto the Polish market in compliance to the Article 32 (Regulation of the European Parliament and Council (CE) No 1069/2009),
- composted or converted into biogas,
- applied to soil without prior pretreatment,
- used as a fuel for combustion with or without prior pretreatment,
- applied to produce other by-products indicated in the Article 33, 34 and 36, and placing on the market in compliance with these articles.

It is worth to emphasize that production of fertilizers or soil improvers predominates. In this case, there is a number of legal requirements to fulfil. Table 1 presents the legislation to be followed when

Table 1
Legislation in force in Poland and European Union regarding natural fertilizers.

	Legislation in force
Polish legal acts	Act on fertilizers and fertilization of July 10, 2007 (as amended).
	Ordinance of the Minister of Agriculture and Rural Development of July 20, 2018, amending the ordinance on the detailed method of applying fertilizers and conducting training in their use (Journal of Laws of 2018, item 1438).
	Act of 22 November 2013 amending the act on the protection of animal health and combating infectious diseases animals and some other laws.
	Ordinance of the Minister of Agriculture and Rural Development of April 16, 2008, on the detailed manner of applying fertilizers and conducting training in their use (as amended).
	Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of some provisions of the Act on fertilizers and fertilization.
	Instruction of the Chief Veterinary Officer No. GIW Pr – 02010-4/2014 of 14 April 2014 on the rules of conduct of the Veterinary Inspection when supervising the use of organic fertilizers and soil improvers made from animal by-products, derived products or with the participation of these products, and statements of prohibited proteins of animal origin in feeding stuffs.
	Act of 22 July 2006 on feed.
Regulations of the European Union Commission	Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003. regarding fertilizers.
	Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down sanitary provisions for animal by-products not intended for human consumption, and repealing Regulation (EC) No 1774/2002 (Regulation about animal by-products).
	Commission Regulation (EU) No 142/2011 of 25 February 2011 on the implementation of Regulation (EC) No 1069/2009 of the European Parliament and of the Council laying down sanitary provisions for animal by-products not intended for human consumption and implementing Council Directive 97/78/EC for certain samples and items exempted from veterinary checks at borders under this Directive.

producing natural fertilizers (Kukier et al., 2016).

On a national level, any natural fertilizer which was produced should obtain an opinion regarding the fulfillment of requirements on pollution and the quality of the obtained natural fertilizer, e.g. from poultry manure. In Poland there is a number of certified institutions which test and evaluate fertilizers (e.g. the Institute of Soil Science and Plant Cultivation State Research Institute). Tests/opinions on suitability for use are carried out by the Institute of Soil Science and Plant Cultivation State Research Institute, Institute of Technology and Life Sciences in Falenty, Research Institute of Horticulture in Skierniewice, Forest Research Institute in Warsaw.

Whereas tests assessing the impact on human and animal health, the environment, through tests sanitary and biological tests. These tests are carried out by the following institutions: the National Veterinary Institute - National Research Institute in Puławy (issues opinions on the lack on harmful effects on animals and veterinary status), the Institute of Rural Medicine Witolda Chodźki in Lublin (issues opinions about lack on harmful effects on human health), the Institute of Environmental Protection in Warsaw (issues opinions about lack on harmful effects on environment) (Kukier et al., 2016).

3. Characteristics of poultry manure

Poultry manure is one of the major animal by-products generated in production of poultry in Poland. Legal definition of manure as an animal by-product states that this means any excrements and/or urine of farmed animals other than farmed fish, with our without litter (Regulation (EC) No 1069/2009). Table 2 shows the quantities of poultry manure produced by different breeds and groups.

In 2017 the quantity of chicken manure produced in Poland was estimated at 2121750 Mg per year (Polish)Yearbook Statistics Office, 2018) (Statistical Yearbook of Agriculture, 2018).

Poultry manure contains wide range of various nutrients and elements such as nitrogen, phosphorus, potassium, copper, zinc, calcium, cobalt, iron, selenium, molybdenum, manganese and boron. In comparison to other types of animal manure, poultry manure demonstrates higher contents of nitrogen, phosphorus and calcium (Table 3).

The contents of these constituents may differ depending on several factors such as a breeding system, seasonality, a breed type and a production group. For example, chicken manure contains about 68–73% of water, 1.24–2.31% of nitrogen, 0.48–0.68% of phosphorus, 0.36–0.59% of potassium. Nitrogen is present in the form uric acid (40–70%), urea (4–12%), ammonium (4–20%) and nitrogen of feed protein (10–40%). Trace amounts of nitrogen can be also present in the form of, e.g., creatine (Augustyńska-Prejsnar et al., 2018). For example, chicken broiler production in a bedding system can generate 2 Mg per 1000 birds of manure containing 2.8% of nitrogen, 3.0% of phosphorous and 1.5% of potassium. As for laying hens in a bedding system the quantity of manure can reach up to 30 Mg per year – the content of nitrogen, phosphorous and potassium is about 2.4, 2.5 and 1.1%, respectively (Myszograj and Puchalska, 2012).

Table 2
The quantities of poultry faeces per 1000 birds from different breeds and production groups (Augustyńska-Prejsnar et al., 2018).

Poultry species and production groups	Quantities of poultry manure from 1000 birds (kg per day)
Chicken broilers	65
Turkeys	160
Geese for slaughter	200
Ducks for slaughter	190
Laying hens "towarowe" (intensive egg production)	150
Laying hens "rodzicielskie" (intensive egg production)	155

Table 3
Average chemical composition of manure from different poultry breeds and livestock (Agricultural news, 2017).

Manure origin	Nitrogen	Phosphorous	Potassium	Calcium
	kg Mg^{-1}	kg Mg^{-1}	kg Mg^{-1}	kg Mg^{-1}
Chickens	15.0	15.0	8.0	24.0
Geese	5.5	5.5	9.5	8.5
Ducks	8.0	11.0	5.0	13.5
Cows	4.7	2.8	6.5	4.3
Pigs	5.1	4.4	6.8	4.4
Horses	5.4	2.9	9.0	4.3
Sheep	7.5	3.8	11.9	5.8

4. Environmental impacts of poultry production

Production of poultry in various farming systems in Poland poses many threats to natural environment and human health. They include: emission of noise, emission of pollutants into the atmosphere, waste generation, contamination of wastewater and microbial contamination.

Noise emission is related to operations and installations in the poultry farming building (e.g. roof and peak fans). The main source of substances emitted to the environment from the installations are animals kept in livestock buildings. As a result, the following compounds are emitted in the poultry houses: ammonia (NH_3), methane (CH_3), nitrous oxide (N_2O), dust - including suspended particulate matter PM10 and PM2.5, substances created as a result of burning gas for heating purposes: sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and dust. Poultry farms can also generate dimethylamine, carbon dioxide, as well as ketones, aldehydes, organic acids and other odor compounds (Myszograj and Puchalska, 2012). The most environmentally harmful gas produced at poultry farms is ammonia. From the total amount of nitrogen excreted by birds - from 13 to 20% for broilers and from 2 to 20% for laying hens, it is released from the manure into the air in the form of ammonia: direct emissions from hen houses, storage areas for used litter and poultry manure, arable fields in the case of using a poultry manure as a fertilizer. Ammonia released from the litter in the hen house, adversely affects birds, but also negatively impacts on workers.

Intensive production of poultry in Poland faces many challenges, including those relating to handling and managing poultry manure. Poultry manure can pose a potential threat to human health and have a negative impact on natural environment, in particular the quality of water and soil (Myszograj and Puchalska, 2012).

Storage of poultry manure can generate odors and gaseous emissions such as ammonia (Table 4) and methane. It is estimated that the total amount of nitrogen released from chicken manure in the form of ammonia is 2–20% from laying hens and 13–20% from broilers. As for methane emission from 1000 birds, it is generally estimated at 80 kg per year (Mielcarek, 2012). In 2015, the European Union agricultural sector emitted 3751 kilotons of NH_3 and was responsible for 94% of total ammonia emissions in EU (Eurostat, 2018).

What is more, poultry manure can be contaminated with trace

Table 4
Emission of ammonia on the farms resulted from poultry manure storage.

	Emission from 1000 birds in kg per year				
Type of waste	Laying hens	Broilers	Ducks	Geese	Turkey
Chicken manure (no bedding)	No data	220	680	350	950
Poultry litter (faeces and urine, with bedding)	480	No data	No data	No data	No data
Slurry (fermented urine and little faeces, bedding)	480	No data	No data	No data	No data

elements which is directly attributed to feeding and breeding procedures. Usually, zinc (Zn) and copper (Cu) are used as animal feed supplements to increase the feed efficiency and decrease morbidity. Wieremiej (2017) reported that poultry manure can contain 3900 mg/kg of Fe, 427 mg/kg Zn, 13 mg/kg Ni, while cattle manure contains about 150 mg/kg of Zn. Another issues of poultry manure application is connected with migration of pathogens and air pollution, especially odors and greenhouse gases emission (Wieremiej, 2017).

Poultry production can be the source of specific microbial contamination. The characteristic microclimate of the poultry house environment is associated with high air humidity, high temperature, reduced air exchange volume and solid elements such as: drinking bowls, feeders, feeders, perches, nests, litter, feed and animals. Generally, poultry source is the most important source of bioaerosols (Stuper-Szablewska et al., 2018). In an industrial poultry farm, potential threats to human health include: *Chlamydia* spp., virus H5N1, *Salmonella enteritidis, Salmonella typhimurium, Bacillus anthracis*; *Listeria monocytognes*; *Staphylococcus aureus, Streptococcus* sp., *Cryptococcus neoformans, Aspergillus (A. niger, A. nidulans, A. ochraceus), Penicillium notatum, Penicilliums* sp., *Cladosporium* sp., *Alternaria* sp., *Candida albicans*. The occurrence of *Salmonella* at poultry farms is strictly monitored by the General Veterinary Inspectorate in Poland. The possible route of transfer of bacteria with poultry meat is also estimated. Each case of *Salmonella* detection in meat is send to Rapid Alert System for Food and Feed. The *Staphylococcus* content is an indicator of bacterial air pollution. The threat is the possibility of transporting pathogens in the air. The emission from the source with the windbreak can be at least 500m, and the concentration of *Staphylococci* at this distance may obtain even 4000 CFU/m^3 (National Chamber of Poultry Producers and Feed, 2019). The source of contaminations can be also surrounding soil. Trawińska et al. (2016) in the conducted research near the reproductive chicken farm showed the presence of *E. coli* and *Proteus* spp.

According to the report published Supreme Audit Office (2014) four main risks were identified, i.e.: odors, contamination of water, over-fertilization of soil, and chemical and microbiological contamination of food (e.g. residues of antibiotics and growth hormones) (Western Center of Social and Economic Research, 2018).

5. Risks related to managing poultry manure

Poultry manure is rich in nutrients, and thus could be directly applied to soil as a soil improver or after being processed, e.g. through composting as a fertilizer or a compost. However, poultry manure can also contain various contaminants which are potential risks to soil and living organisms. Table 5 presents the list of key contaminants which were detected in poultry manure.

Antibiotics used in poultry treatment can have direct implications to poultry manure. Until 1969, antibiotics were used intensively in Poland. This resulted in antibiotic resistance in poultry. Since then, the use of excessive amounts of antibiotics that have stimulated animal growth has been gradually withdrawn. Farmers could only use antibiotics that were supposed to reduce pathogen infections and other medications could be used only after consulting a veterinarian. In 1997–1999, medicine such as avoparcin, zinc bacitracin, spiromycin, virginiamycin, and tyrosine phosphate were withdrawn from use in the European Union. In 2006–2007, however, all antibiotics were banned except therapeutic drugs, only the possibility of application coccidiostats. Despite the prohibition introduced in 2007 on the use of antibiotics that stimulate growth, the effects of excessive use are still being observed. This is manifested by pathogens that have strong defense mechanisms transmitted through inheritance. Medicine resistance became a problem that has still not been effectively eliminated. New antibiotics are effective only for a short period. Then, pathogens quickly specialize in new defense mechanisms (Zalewska et al., 2017).

In the literature, we can find data on the content of antibiotics in animal organisms and the amount of their excretion along with faeces.

Table 5
The key contaminations detected in poultry manure.

Contamination type	Specified	Reference
pathogens, including bacteria	*E. coli, Salmonella, Staphyloccocus, Campylobacter, Clostridium, Listeria, Bordetalla, Corynebacterium, Globicatella, Mycobacterium, Streptococcus, Actinobacillus*	Kyakuwaire et al. (2019)
fungi	*Penicillin* spp *(59.9%), Alternaria (17.8%), Cladosporium (7.1%), Aspergillus (5.7%)* *Aspergillus, Scopulariopis, Penicillium*	Viegas et al. (2012) Pascal et al. (2011)
helminthes sp.; detected in poultry manure are non-parasitic in mammals	*Ascaridia galli, Heverakis* sp., *Raillietina* sp. *Davainea* and *Rallietina* sp.	Chee-Sanford et al. (2009) Smith (2018)
parasitic protozoa	*Cryptosporidium, Giardia* spp.	Bowman et al. (2000)
viruses	Avian Influenza (AI)	Tsapko et al. (2011)
antibiotics and antibiotic-resistant genes	50–100% resistance to nalidixic acid, sarafloxacin, ampicillin, tetracycline, amoxicillin, ceftiofur, sulfonamide, clindamycin, erythromycin, enrofloxacin eight ARGs (*tetA, tetG, tetM, tetO, tetQ, tetW, sulI, and sulII*) in the manure-amended soil 0.9% in aminoglycosides, 6% in macrolides, and up to 59.6% in tetracyclines; the most significant is the resistance of salmonellas and campylobacters to tetracyclines (5.6–82.4% and 1–87.5%, respectively) and quinolones (3.6–94.1% and 3.96–96.3%, respectively)	Kyakuwaire et al. (2019) Tang et al. (2015) Laloučková and Skřivanová (2019)
growth hormones such as egg and meat boosters	endocrine-disrupting compounds (EDCs); broiler litter contains 17β-oestradiol, oestrone, oestriol, and testosterone thatcan persist in poultry litter	Bolan et al., (2009)
heavy metals and metalloids	As, Co, Cu, Fe, I, Mn, Se, Zn; used to prevent deficiencies and diseases, improve weight gains and feed conversion, and increase egg production	Bolan et al. (2009)
pesticides	2-Chloro-1-(2,4,5-trichlorophenyl) vinyl dimethyl phosphate bifenthrin, imidacloprid and fipronil	Kyakuwaire et al. (2019) Ong et al. (2017)
coccidiostats	sulphaquinoxaline, decoquinate	Hobson-Frohock and Johnson (2006)

Table 6
The use of antibiotics in breeding of animals in 2012 in the European Union.

Name of antibiotics	Amount [%]
Tetracyclines	33.4
Penicillins	25.5
Sulfonamides	11
Macrolides	7.5
Polymyxins	6.6
Aminoglycosides	3.5
Lincosamindes	3.5
Pleuromutillins	2.8
Fluoroquinolones	1.9
Trimethoprim	1.6
Others	2.7

Table 6 shows the content of antibiotics in the bodies of animals that are intended for food purposes, data from 29 European Union countries (Quaik et al., 2019).

Although residues of veterinary medicines can be found in poultry manure at concentrations which do not have a greater direct effect on human health in the food chain (soil, plants, animal, man), the presence of these residues has significant consequences for thriving of the soil microflora. The most pressing problem is growing drug resistance, including antibiotic resistance of microorganisms in the environment. In addition, the microbial resistance is enhanced due to metals/metalloids presence (Kyakuwaire et al., 2019). It is estimated that up to 75 percent of the antimicrobials used in poultry are excreted (Baloučková et al., 2019). The main poultry parasites such as *Cryptosporidium* and *Giardia* spp. can simply spread from manure to water resources and can persist in the environment causing danger to animals and humans (Bowman et al., 2000). Research on the influence of steroids on endocrine disruption confirms fish reproductive disorders nearby the runoff from poultry manure amended fields (Gerber et al., 2007). In the group of contaminants present in poultry manure, insecticides can also be found. They are used in the control of *Dermanyssus gallinae* (also known as the red mite) which is an ectoparasite of poultry and has been implicated as a vector of several major pathogenic diseases. Thus, fipronil (Table 7) is in usage in controlling insects (Ong et al., 2017), although its use in poultry production in Poland is prohibited.

Not all countries comply with the law regarding the use of medicines in animal husbandry. Legal gaps that allow medicine use are still being exploited. Also, banning the use of medicine completely will not solve the problem right away. Medicine-resistant pathogens, new antibiotics, accumulation of drugs in soil, water is a challenge to study over the next years.

Apart from antibiotics, pesticides can have also direct implications on the application of poultry manure. One of the pesticides, more specifically an insecticide, that has a very good insecticidal effect is Fipronil. It was introduced to the market in 1993. Especially effective against parasites that occur on the skin and feathers of poultry.

However, similarly to antibiotics, this pesticide accumulates in the body, eggs, animal droppings, and sewage. Thus, posing a threat to soil and water when poultry manure is applied to soil as a fertilizer. Fipronil has been banned in the European Union since 2013 due to its harmfulness to humans and animals. The lethal dose for humans is $LD_{50} = 92$ mg/kg, for rodents 24 mg/kg and for insects including flies and pollinating insects 0.13 mg/kg. While, the limits for insecticide (the metabolite of fipronil - de-sulfinyl fipronil) in the EU are, for humans (daily intake) 0.0002 mg/kg, while in products such as eggs 0.005 mg/kg (i.e. 5 ppb per egg). Despite the legal regulations, a big problem with this pesticide is in the USA and China, where animal production is much higher than in the EU.

For example, in China, 2.875 billion tonnes of organic waste is generated annually from poultry production alone (Hu et al., 2019; Stafford et al., 2018). Different doses of pesticide and their accumulation in selected poultry tissues depend on the time of exposure to the pesticide, dose, frequency of administration, type of animal. Table 7 gives examples of pesticide content in poultry tissues (Stafford et al., 2018). The analysis was performed 28.975 days after the start of dosing.

Fipronil is harmful to living organisms due to irreversible contamination with this pesticide. There is little information regarding the decomposition time in the body of this insecticide and how it affects the innate traits in animals.

Table 7
Different doses of the selected pesticide and its accumulation in the selected poultry tissues.

Dose of Fipronil	Tissues of poultry, pesticide accumulation [ppb]		
	Egg yolk	Peritoneal Fat	Skin
(10 ppm) - prior to feeding, every 24 h, for 28 days	30,000	56,000	17,000
(2 ppm) - prior to feeding, every 24 h, for 28 days	7020	12,000	3900
(0.5 ppm) - prior to feeding, every 24 h, for 28 days	180	290	100

6. Common practices for management of poutlry manure

The most common practices for management of poultry manure in Poland include the applications of poultry manure for soil (land spreading of unprocessed poultry manure, production of fertilizers and soil improves of different composition and in various forms, e.g. unprocessed poultry manure, granular forms, pellets and composts) and for production of biogas through anaerobic digestion. Examples of soil applications include using poultry manure as an unprocessed organic fertilizer, a feedstock for composting with other agricultural residues to produce compost, as feedstock to be processed into a granulated or pelletised fertilizers and other fertilizers mixed with mulch and minerals (e.g. dolomite, lignite, peat). Ash from combustion of chicken manure, as an addition to fertilizers (Augustyńska-Prejsnar et al., 2018; Kopeć et al., 2014; Staroń et al., 2014). Poultry manure can be used as a fuel (e.g. in a form of pellets) for combustion to recover energy as well as a main substrate for biogas production. Other applications include mushroom production where poultry manure can serve as a substrate/growing media for mushrooms (Łobos and Szewczyk, 2013). Also, recently there is a growing interest in converting poultry manure into biochar that demonstrates some potential for soil and environmental applications (Słodeczek et al., 2017).

Soil applications are the most common practices for managing poultry manure. One of the least energy consuming methods of poultry manure disposal is land spreading. Poultry manure can be used as a soil amendment and fertilizer due to high content of nitrogen (N), phosphorus (P) and trace elements which can improve the physical and biological fertility of soil. Natural (manure) fertilization is the source of essential nutrients for plants. The processes of mineralization of organic compounds contained in natural fertilizers cause beneficial effects on plants with a long growing season, increase the possibility of soil retention and slow decomposition of phosphorus and potassium, and as a source of humus improve the physical, chemical and biological properties of the soil and enrich its microflora. The standard practice before poultry manure soil application is to determine the fertilization dose based on the nitrogen content in soil and in manure. In accordance with legal regulations in Poland and the European Union, the nitrogen dose applied cannot exceed 170 kg per ha per year (Council Directive 91/676/EEC, 1991). It is estimated that yearly generated poultry manure production enables fertilization of 2% agricultural land in Poland (Wieremiej, 2017). The perfect content of C:N:P in fertilizer for biological purposes shall be 100-10-1. Thus, the utilization of poultry manure as a perfect soil fertilizer may require an additional source of carbon (C) to avoid loss of N and P through leaching. This type of fertilizer consists usually 1–14% of C, making the C:N ratio 6–7 (Agbede et al., 2008). The long-standing and repeated poultry manure soil application can result in phosphate and nitrate contamination of surface waters and trace elements accumulation or result in phytotoxic effects on succeeding crops (Agbede et al., 2008; Tańczuk et al., 2019a,b; Tańczuk et al., 2019b). When using natural fertilization, it should be remembered that mineral components potentially available to plants are released gradually over 2–3 years, which means that natural fertilization cannot be applied to a given soil every year. In Poland, and in central Europe natural fertilizers are used in the most optimal four-year cycle which in a way limits the constant possibility of using poultry manure for agricultural purposes. Moreover, improper application of poultry manure can result in soil nutrient imbalance. Thus, the soil nutrients testing is the primary issue concerning the poultry manure application (Wieremiej, 2017).

Although the most common ways of managing poultry manure is to use it for nutrient recovery and application to soil, there are other examples of technologies that would allow conversion of poultry manure into added value products. There is a strong interest in combining different technologies for efficient recovery of nutrients and energy from poultry manure. For example, a patented technology "Transforming Poultry Production" developed by BHLS company allows production of heat and energy through combustion of poultry manure uses as a fuel on a fluidized bed. This technology can be applied on a poultry farm where poultry manure is transported to a biologically safe storage and then conveyed to a fluidized bed for combustion. The remaining ash – which is rich in phosphorus and potassium – can be used for nutrient recovery and transformation. This complex approach has a number of advantages. Primarily, poultry manure is managed on site and used as a fuel to generate heat and electricity that can be utilized for maintenance of poultry houses. This results in reduction of costs of transportation and increase in biological safety (BHLS, 2015).

The literature provides a number of examples demonstrating the methods and technologies for converting of poultry manure in order to recover nutrients and/or energy. They include composting, anaerobic digestion, pyrolysis, drying and other. Table 8 gives an overview of various methods used to process poultry manure with corresponding challenges.

It has to be pointed out that the one of the most common challenge for poultry manure processing is dealing with gaseous emissions. This is particularly the case with composting which leads to nitrogen loss through ammonia emission which can range from 13 to 70% (Hao and Benke, 2008; Shin et al., 2019). It was estimated that within nitrification-denitrification of poultry manure the emission of N_2O ranges from 0.1 to 0.8%, CO_2 ranges from 52 to 80% and CH_4 ranges from 0.04 to 0.34% (Melse et al., 2008; Hou et al., 2016).

7. Promising solutions for poutlry manure management

Although several technologies are already available for managing poultry manure, there are more promising solutions that are currently being developed in some of the Polish research institutions. Those solutions are based on a complex approach to manage poultry manure on site but also aim at improving the efficiency of the existing technologies and to develop new/improved products from poultry manure. Table 9 presents some of the examples of recent research projects conducted in Poland.

7.1. Anaerobic digestion

One of the promising methods for managing poultry manure for energy recovery is production of biogas through anaerobic digestion. The high content of biodegradable organic matter and high buffer capacities of chicken manure is a very interesting substrate for anaerobic digestion (AD). According to literature, chicken manure is characterized by the content of dry organic matter from 63 to 80% total solids (TS), production of biogas: 250–450 m^3/Mg VS and 60% (volume) of methane content in biogas (Sadecka et al., 2016). Nonetheless, separate AD of this waste may be ended failure due to low carbon to nitrogen ratio in the feedstock (oscillated around 5–10) as well the ammonia accumulation during the process, which is results anaerobic decomposition of uric acid and undigested proteins, namely two main forms of nitrogen in chicken manure (Duan et al., 2018; Yuan et al., 2016; Abouelenien et al., 2010). Ammonium ions and free ammonia are main by-products from degradation of nitrogenous matter, both forms may inhibition of methanogenic activity on following ways: 1) cause a potassium imbalance and/or proton deficiency; 2) inhibition of a specific enzyme reaction; 3) alter the intracellular pH, 4) increase of maintenance energy requirement (Chen et al., 2008). Additionally, high content of hydrogen sulfide in biogas decrease the utility of the AD and forces treatment of biogas before further use for example in co-generation unit (Tańczuk et al., 2019a,b; Tańczuk et al., 2019b).

For these reasons, in recent years, researches are focused on the enhancement of effectiveness of the process. From the available intensification options for anaerobic digestion of chicken manure, two seem particularly interesting, namely co-digestion (AcD) with other organic wastes and pre-treatment of the feedstock before AD. Generally, additions of another organic waste to the anaerobic digester causes: a) increase degradation degree of treated substances and improved biogas and methane yields, b) support in establishing the required moisture content of the digester feed (dilution with water or wastewater is one the main strategy to eliminate the negative impact ammonia on AD), c) improve nutrient balance and adjustment of C/N ratio in feedstock, d) increase load of biodegradable fraction as well as content of macro- and micronutrients, e) higher dilution of toxic compounds. Due to this strategy opens up new possibilities for disposal of organic waste – especially those wastes, which would be difficult to digestion separately (e.g. pig/cow waste slurry) (Mata-Alvarez et al., 2014; Grosser, 2017). The suitable co-substrates for poultry manure are C-rich waste such as: other types of manure like cattle manure (Callaghan et al., 2002), lignocellulosic residues (Neshat et al., 2017), agricultural wastes (Abouelenien et al., 2014) or organic fraction of municipal waste (Matheri et al., 2017), straw (Li et al., 2014), leaves and weeds, hay, haulm tomatoes, haulm cucumbers, grass, corn silage (Sadecka et al., 2016). Agro-industrial waste are the most used as co-substrate. However, due to their seasonality, new groups of wastes are still being sought that could be processed together with manure. Table 10 summarizes some results of poultry manure co-digestion with different wastes research results.

The effect of introducing external additives on the anaerobic digestion of chicken manure was also studied. For example, Ma et al. (2018) found that compared to the control sample, addition of thermally modified bentonite at 300 °C into reactor increased cumulative methane production up to 41%. Mentioned addition had also positive impact on the buffering capacity of fermentation broth (lower fluctuation of pH than for the control) concentration of soluble salts (lower than for control – it should be kept at a moderate level, because this strategy prevents inactivation of methanogenic archaea as well as inhibition of the transport of metabolite and nutrients) as well as total content of ammonia nitrogen (TAN) and free ammonia (the TAN and FA concentration reduction was improved by 10% and 25%, respectively). Likewise, Pan et al. (2019) observed that the addition of biochar improve the buffering capacity of the anaerobic digestion system as well as reduce the content of TAN, FA and soluble salt. They also found that about 69% of the methane yield was increased for reactor treating chicken manure owning to biochar addition. In turn, Kougias et al. (2013) demonstrated that addition of 10 g/l natural zeolite enhanced the biogas production. In comparison with the control reactor (without zeolite addition) about 109.75% increased methane production was noted. Due to the fact, that the high concentration of ammonia is most often indicated as an agent inhibiting the anaerobic digestion, methods to removal of mentioned compound from feedstock and/or anaerobic digester have been also the subject of studies. Described in literature, the approaches to mitigate accumulation of ammonia into anaerobic digester include following solutions: 1) stripping of the anaerobically digested effluent (Abouelenien et al., 2010; Guštin et al., 2010), 2) trace elements supplementation (for example 0.2 g/m^3 of selenium addition stimulated methane production even at high content of hydrogen sulfide and TAN as well as moderate organic loading rate which was possible to occurred through syntrophic acetate oxidation) (Molaey et al., 2018), 3) struvite precipitation, 4) ion exchange, 5) membrane separation (Wang et al., 2018), 6) dilution of the feedstock (typical content 20–25% TS) to 0.5–3.0% total solids (Duan et al., 2018; Kelleher et al., 2002).

However, in Poland raw poultry manure as a main feedstock is used very rarely. There is only one case of a poultry farm equipped with biogas installation in Poland. This installation of power rating of 25–30 kW on the farm located in near Pszczyna city. This installation is fed

Table 8
Challenges of converting poultry manure through selected methods.

	Methods	Case	Effects	Challenges	References
Composting					
1	Composting poultry litter	Reducing ammonia emissions by adding zeolite, coconut and clay.	The addition of zeolite and coconut fibers effectively reduced ammonia emissions during composting.	The wetter the material, the longer the drying process and the further the poultry litter treatment.	Kelleher et al. (2002)
2	Composting poultry manure with cassava peels	Chemical and biological properties of compost from poultry manure and cassava peels	Were receive compost rich in nutrients. At the end of the process, the total N in the compost was also reduced.	Problems with reaching higher temperatures may occur, which may result in a lack of properly compost hygienization.	Ojo et al. (2018)
3	Composting combined with drying	Obtaining market products.	Composted and dried chicken manure had effects on rooting young cuttings, mycorrhization and strengthening the root system, insect eradication, biological protection.	Overcoming the issue with production costs.	ASTVIT NE/128/2010
Pyrolysis					
1	Chicken litter pyrolysis	Low-temperature pyrolysis based on German technology WSK Anlage GmbH.	Possibility of using biochar as a soil improver or for forest reclamation.	Investment costs - the construction of an industrial low-temperature waste biomass pyrolysis plant has financial justification only if a subsidy is obtained for the investment; (the economic assessment of the functioning of the installation for biochar production from chicken manure was carried out for installations with a biochar capacity of 420 tons/year).	Słodeczek and Głodek-Bucek (2017)
2	Poultry manure pyrolysis	Chicken manure processing at temperatures in the range of 300–600 °C.	The production of organic biochar for agriculture should be carried out at temperatures of 300–500 °C. The increase in temperature caused an increase in pH, EC, BET, and biochar stability.	Reduction of production efficiency, nitrogen content (loss of 81.2% nitrogen content at 500 °C), OC, CEC with increasing temperature.	Song and Guo (2012)
3	Pyrolysis broiler litter	Processing broiler litter in temperature 680 °C.	High ash content, high pH affects the use of biochar as preparation for improving soil condition (liming agent). High exchangeable cations (nutrient uptake). The produced biochar was characterized by aromaticity; therefore, it was stable, had potential for use in the soil for carbon sequestration for long periods of time (low H/C, low O/C).	–	Srinivasan et al. (2015)
4	Pyrolysis poultry manure	Processing poultry manure in temperature 200–500 °C.	As the temperature increased, the pH, CEC, content of P, K, Fe, Mn, Zn, Cu increased. The increase in temperature promotes the formation and strengthening of the aromatic structure. Biochar at 400 and 500 °C was strongly alkaline - it may be useful for acidic soils. Pyrolysis temperature 300 °C - biochar suitable for calcareous soils. Temperature> 300 °C - biochar for agricultural use in acidic soils.	An increase in temperature caused a decrease in production efficiency. Biochar at 400 and 500 °C was strongly alkaline - may limit its use in calcareous soils. Due to the high EC, its use may be limited in salt-sensitive crops.	Bavariani et al. (2019)
5	Pyrolysis poultry litter	Processing poultry litter in temperature 350 and 700 °C	Poultry litter biochar grossly increased Mehlich-1 extractable P and Na concentrations. Creation of designer's biochar may be possible with distinct quality traits that can improve discrete soil chemical and physical properties.	–	Novak et al. (2009)
6	Pyrolysis poultry manure	The use of biochar from chicken manure for microcystin-LR sorption.	This biochar has huge potential as cheap, durable MC-LR sorbents from water. Biochar from animal faeces (e.g. poultry), due to their higher ash content, have better sorption properties of organic pollutants (interaction of ash content with organic matter in biochars). The	–	Li et al. (2018)

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Table 8 (*continued*)

	Methods	Case	Effects	Challenges	References
			mineral ash content may provide additional binding sites for cations and/or anions for IOC adsorption.		
7	Pyrolysis poultry litter	Processing poultry manure in temperature 550 °C	Biochars demonstrated higher and stronger retention of Cd due to the mineral phase. Mineral phases of biochar can contribute to Cd sorption by electrostatic reaction, ion exchange, surface complexation and precipitation.	Biochars had very low thermal stability and contained mostly labile non-carbonized organic carbon (OC) and very small amounts of stabile carbonized OC.	Qi et al. (2017)
Anaerobic digestion					
1	Anaerobic digestion	Laboratory, pilot scale mono-digestion of poultry manure or co-digestion of poultry manure with different organic waste (e.g. corn stover; cheese whey wastewater, maize silage) – processes were conducted in different types of reactor (e.g. continuously tank reactor, bath reactor), temperature regime as well as operating parameters such as hydraulic retention time and organic loading rate.	1) reduction emission the main greenhouse gas (methane) into atmosphere due to fact that decomposition of manure is carry out in controlled condition, 2) energy recovery (methane yield ranges from 0.01 to 0.5 m^3/kg VS), 3) valuable products such as biogas as well as digested sludge which after proper stabilisation may be used as fertilizer, 4) reduction in the consumption of fossil fuel 5) introduction co-substrate into reactor treating manure causes increases biogas/methane production and the stability of reactor as well as allows for a better nutrient balance, 6) removal of nuisance odors.	1) high content of ammonia nitrogen can inhibition the performance a process 2) acclimation of microorganism to high ammonia concentration 3) integrated anaerobic digestion with different technology (e.g. pyrolysis – possibility increase energy recovery; stripping – removal ammonia from waste or liquid fraction of digestate) 4) scum formation 5) start-up process 6) transportation, collection and storage of manure and co-substrates 7) the fate of organic micro-pollutants (e.g. insecticide) in the anaerobic digestion process - degradation in anaerobic condition as well as impact on process efficiency.	Sakar et al. (2009) Abbasi et al. (2012) Ong et al. (2017) Hu et al. (2019) Carlini et al. (2015) Böjti et al. (2017) Li et al. (2014) Nasir et al. (2012)
2	Methane fermentation	Production of biogas	One of the methods of managing the excess chicken manure. The biogas produced may be sufficient for the farm's own needs, e.g. heat and energy demand.	This fuel can be a source of polycyclic aromatic hydrocarbons and other toxic compounds, which, when produced in excess, can be hazardous to health. Therefore, appropriate filters should be used to reduce emissions of harmful substances.	Augustyńska-Prejsnar et al. (2018)
3	Anaerobic digestion	Dry anaerobic digestion with poultry manure	Recirculation from top to bottom is recommended. The process made it possible to obtain proper methane efficiency.	The high nitrogen content in poultry manure inhibits the digestion process. The use of a higher content of liquid inoculum allowed the process to continue.	Rajagopal and Massé (2016)
Drying					
1	Dried poultry litter	The samples were homogenized, then were placed on the room (room temperature) where they were allowed to dry for 63–64 months.	The natural drying process (64 months) causes a reduction of ammonia and organic phosphorus dissolution in water.	Natural drying is a long process. It depends on the temperature, amount of drying mass. However, drying with a dryer introduces additional energy costs.	Stefan Hunger et al. (2008)
2	Drying poultry manure	Poultry manure with rice husk was sun-dried and then converting to granulate.	By drying and grinding chicken manure, the unpleasant smell is reduced. It could also be used in the form of granules as a fertilizer.	Pellets that were extrusion in the SRF (slow-release fertilizers) machine enabled a longer release of nutrients. But it is a more energy-intensive process than producing SRF granules.	Purnomo et al. (2017)
Pelletizing					
1	Pellet from poultry manure	Utilization of chicken manure to reduce the release of significant amounts of nitrogen into the environment.	The production of pellets from poultry manure allows the reuse of nutrients.	Costs associated with manure transport to more distant regions are a challenge.	Hayakawa A. et al. (2009)
2	Pellet from poultry manure	Production of pellet from rye straw and chicken manure	The more chicken manure than straw, the harder the pellets were.	The higher the chicken manure content, the longer the drying time.	Zdanowicz and Chojnacki (2017)
3	Pellet from poultry litter.	The use of poultry litter in the form of pellets to improve soil properties	The effect of poultry litter pellets on the soil on which cotton *(Gossypium hirsutum* L.*)* was planted. Granulated chicken manure positively affected soil moisture retention, infiltration, and increased aggregate stability.	The challenge is to minimize the loss of nutrients and carbon to the environment.	Feng et al. (2019)
4	Pellet from poultry litters	Animal feed ingredient.	The use of granulated poultry litter as a source of protein in the diet of growing meat goats.	There are not many references in the literature to using poultry litter to goats feed and comparing the results obtained.	Jackson et al. (2006)

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Table 8 (*continued*)

	Methods	Case	Effects	Challenges	References
5	Granulation	Obtaining market products	Dry granulate form facilitates its application and storage. It is devoid of unpleasant smell and looks aesthetically.	Limited stability of the fertilizer and concerns about the efficiency of application and consumer concerns about the safety.	FERTIKAL NE/321/2016 Eko NE/387/2017 (Fertilizers, 2018)
Other					
1	Filler for cement mortars	Connection of Portland cement, hydrated lime and sand with a small amount of chicken poultry manure.	Chicken manure can be a filler in cement mortar.	Due to the low pH of chicken manure 3–4, it should be used at a dose of no more than 25%, because a higher content negatively affects cement binding.	Sobczak (2008)
2	Substrate used in growing media for mushrooms	The mixture (straw, rea gips, chicken manure, and water) is fermented, then specialized treatments are performed, and the substrate is ready after a few days.	Obtaining high quality substrates for mushrooms. By managing plant, industrial and animal waste.	The challenge is to produce a substrate that will be economically viable and have the desired product characteristics.	Lobos and Szewczyk (2013)
3	Processing for feed	1. Composting poultry litter under cover 2. Drying chicken manure 3. Ensilage of broiler litter with corn	Thermal treatment reduces pathogenic microorganisms. Waste in the form of chicken manure can be used in nutrition. Practice allowed, among others in the United States.	The challenge is to produce animal feed that meets the sanitary and veterinary requirements through these practices.	https://www.ppr.pl/wiadomosci/edukacja/zaleznosc-miedzy-nowoczesnymi-systemami-2924, (accessed 11 January 2002)
4	Poultry manure combustion in fluidized bed furnaces	BHSL has developed and patented a technology that uses Fluidised Bed Combustion (FBC) combustion to convert chicken manure into heat and electricity for a poultry farm.	Low carbon solution.	Installation costs and lack of interest among breeders.	http://www.bhslhydro.com/wp-content/uploads/2015/03/BHSL-How-it-works_Polish-Version.pdf (accessed 10 April 2019)
5	Gasification	Production of syngas from chicken manure.	Gasification of a chicken manure provides generation of combustible syngas with the lower heating value – 2.0 MJ/m^3 in case raw, pre- dried chicken manure. In case of chicken manure pellets its 2.7 MJ/m^3.	Increasing the share of wood biomass significantly increases the calorific value of syngas. Fraction and ash content require further research to define reactor suitable for co-gasification of analyzed fuel blends	Tańczuk et al. (2019); Tańczuk et al. (2019b)
6	Co-combustion	Possibility of using laying hens manure burned separately or with gas-flame coal	Biomass content increase the reduction of the ignition temperature was observed, thereby increasing of the reactivity of the sample	–	Junga et al. (2017)
7	Biomass energy from poultry manure	Chicken manure as an alternative to the shortage of energy source and high costs of using conventional energy sources.	Production of energy and heat in locations near farms.	Biomass transport costs often limit the profitability of the project.	Dalólioa, F.S. et al. (2017)
8	Combustion of poultry litter	Combustion of chicken litter can provide heating of poultry houses, energy.	Ash from combustion, is light, sterile and easy to transport. Can be used for fertilizing purposes	The challenge is the low temperature of ash from manure (ash fusion), which can be problematic in standard grate combustion applications.	Kelleher et al. (2002)
9	Landspreading of unprocessed poultry manure	Solid manure, droppings slurry mostly for oilseed and protein crops production.	Poultry droppings are often dried and transported to other regions; implementation of a maximum 170 kg N/ha in vulnerable zones is a restriction. Poultry manure is mostly spread on cereal land.	Forbidden during certain periods or on certain land that would otherwise lead to environmental impact via run off or by leaching of the applied nitrogen and phosphorous; Incorporation within 24 h.	Loyon (2018)
10	Production of fertilizers	Poultry manure mixed with rice husk dried and milled, mixed with a binder (starch) and nitrogen source (urea), and then compacted using screw extruder and pan granulator.	Slow release fertiliser (SRF) on plants is advantageous - provides uniform growth.	Pelletised SRF using extruder has longer capability in retaining the nutrient content. Nutrient release of SRF and also other factor such as energy requirements should be properly considered.	Purnomo et al. (2017)

with: chicken droppings (laying hens): (690 tons/year), pig manure (320 ton/year), maize and grass silage (365 ton/year). In turn, in larger installations with the capacity of up to 1 MW, poultry waste are co-digested with agro industrial wastes (Tańczuk et al., 2019a,b; Tańczuk et al., 2019b; BioEnergy, 2015).

In 2018, near Ballymena in Country Antrim at Tully Quarry in North Ireland, the first installation poultry manure anaerobic digestion was operating. Feedstock before digestion are pre-treatment using technology NiX® (Nitrogen Extraction). The installation may be fed up to 40,000 tonnes of poultry manure per year and may delivered 3 MW of electrical energy. The anaerobic decomposition is a two stage process and it is conducted in four digesters. The whole process takes around 45 days (Martin, 2018; McCullough, 2018).

7.2. *Pyrolysis*

Poultry manure can be also processed through thermal treatment (Kelleher et al., 2002) such as combustion or pyrolysis to recover energy and produce added value products. Poultry manure as a substrate has a potential for energy production in e.g. biomass fed power generation

Table 9
Selected recent research projects on managing poultry manure in Poland (public funding).

Research Institution	Project title	Description
Poznań University of Life Science (project funded by National Science and Research Centre, 2016–2019)	Innovative technology of fermentation of poultry manure subjected to reduction of nitrogen content through precipitation of uric acid	Conversion of poultry manure and whey through methane fermentation for stable and efficient production of biogas (Innovative technology of fermentation of poultry manure, 2016).
Ganbare Sp. z o.o. (project funded by National Science and Research Centre, 2017 – ongoing)	Soil improver	Production of a soil improver from organic waste and animal manure, primarily poultry manure, that would allow improvement of soil structure and activation of mineral components (Soil improver, 2019).
NEMO – Research and Development Centre, Sp. z o.o. in Zielona Góra (project funded by National Science and Research Centre, 2016–2019)	Novel production of energy in biogas plant through utilization of poultry manure with the conversion of plant substrate into algae	Development of innovative technology for production of energy from poultry manure and co-substrates in agricultural biogas plants (Novel production of energy in biogas plant, 2015).
Częstochowa University of Technology(project funded by European Union's Horizon, 2020 research and innovation programme under grant agreement No [773,682])	Nutri2Cycle	Technologies for recovery of nutrients and energy from poultry manure through composting, pyrolysis and anaerobic digestion (Nutri2Cycle, 2018).

plants (Billen et al. 2015, 2017; Junga et al., 2017). Also, the ash generated from combustion is a source of valuable constituents such as phosphorous and potassium (Luyckx et al., 2019; Kaikake et al., 2009), as a feed additive for chickens (Blake and Hess, 2014) or as a soil improver or a fertilizer (Billen et al., 2015; Komiyama et al., 2013). Thermal processes are often applied to poultry manure to produce liquid (Midgett et al., 2012; Agblevor et al., 2010) or gaseous (Tańczuk et al., 2019a,b; Tańczuk et al., 2019b) fuels.

Recent studies and reports show that there is also an increasing interest in converting poultry manure through pyrolysis into biochars which could demonstrate a wide range of properties, and thus various applications (Qi et al., 2017; Li et al., 2018; Novak et al., 2009; Bavariani et al., 2019; Song and Guo, 2012; Srinivasan et al., 2015).

Specific properties of biochars produced from a different substrates indicate that those products of pyrolysis can be applied to improve soil properties (Zhao et al., 2018; Ferreira et al., 2018; Czekała et al., 2019), to remove organic and inorganic contaminants from various media (Dai et al., 2019; Ahmed and Hameed, 2018; El-Banna et al., 2018; Regkouzas and Diamadopoulos, 2019), to mitigate ammonia emissions and nitrogen loss during composting (Wang et al., 2018; Sanchez-Monedero et al., 2018; Janczak et al., 2017; Malińska et al., 2014; Ahmed and Hameed, 2018). The potential effects of biochars result from the properties of a substrate and process parameters such as pyrolysis temperature (Li and Chen, 2018; Bavariani et al., 2019; Wystalska et al., 2018; De Bhowmick et al., 2018; Bavariani et al. 2019, 2019; Vaughn et al., 2018, Song and Guo, 2012). With the change in temperature of the pyrolysis process also the properties of biochars change. These properties include pH, elementary composition, surface area, porosity, type and quantity of functional surface groups or stability Li et al., (2017), Hung et al. (2017), Hasnan et al. (2018), Zhao et al., (2018), Song and Guo, 2012, Li and Chen (2018), Giudicianni (2017), Manyà et al., 2018).

Recent studies report that poultry manure can be converted to biochars in the range of temperatures of 200–700 °C (Qi et al., 2017; Li et al., 2018; Novak et al., 2009; Bavariani et al., 2019; Song and Guo, 2012; Srinivasan et al., 2015) resulting in various properties of biochars (see Table 11).

The literature provides a number of studies on potential applications of poultry derived biochars which can be used as amendments for composting (Khan et al., 2016), materials for immobilization of selected heavy metals (Uchimiya et al., 2012), sorbents (Uchimiya et al., 2010; Li et al., 2018; Qi et al., 2017), soil improvers (Srinivasan et al., 2015; Bavariani et al., 2019; Novak et al., 2009) or additives for carbon sequestration (Srinivasan et al., 2015). However, the literature does not provide sufficient analysis of carbon, nitrogen and phosphorous cycles during the process of pyrolysis, and thus nutrient transformation and loss. Any literature on scaling up pyrolysis of poultry manure has not been reported. Most of the work has been done on laboratory or pilot scale.

8. Conclusions

Poland is one of the leading poultry producers in Europe and as such has to face many challenges with managing the quantities of poultry manure generated at Polish poultry farms. The number of poultry farms in Poland has been increasing which resulted in even higher quantities of poultry manure that need to be properly managed. It has to be pointed out that one of the main challenges of poultry management is handling and managing poultry manure in small and medium-sized industrial farms located in non rural areas in Poland. Excessive quantities of poultry manure require transportation, storage and further handling and/or processing. Uncontrolled management of poultry manure can cause emission of methane, carbon dioxide and ammonia into the atmosphere. Poultry manure applied to soil in excess and in uncontrolled manner can pose a serious threat to soil and water environment.

Poultry manure is rich in nitrogen but also contains significant quantities of phosphorous and potassium, and thus is used to produce fertilizers and soil improvers which are available in granular forms, pellets or as composts. In rural areas, still the most common practices of management of poultry manure are related to soil applications. However, since there is limited area for safe land spreading of unprocessed poultry manure, therefore it has to be handled using different methods.

Apart from predominating soil applications, poultry manure is used to recover energy. Present solutions are based on combustion of poultry manure in thermal installations to produce heat and electricity. It has to be emphasized that currently in Poland there is a growing interest in converting poultry manure into biogas through anaerobic mono and co-digestion. However, there is a number of challengers related to this technology which are now investigated by researchers in many research institutions.

Ongoing research projects conducted in Polish research institutions have the ambition to provide more centralized solutions for nutrient and energy recovery from poultry manure. Those solutions attempt to combine existing technologies (composting, pyrolysis, anaerobic digestion) and develop a biorefinery platform for poultry manure. Closing carbon, nitrogen and phosphorous loops in management of poultry would require dealing with e.g. nitrogen loss and ammonia emission during composting, ammonia inhibition during anaerobic digestion and nutrient transformation and losses in pyrolysis. Nowadays, research has been driven by the concept of poultry biorefinery – an approach to manage and process poultry manure on site for energy and nutrient recovery and production of added value products. However, more work is needed to verify and upscale this concept in various economic conditions, farm typologies and legal and environmental requirements.

With reference to the outcome of this study we can conclude that:

Table 10
Summary of anaerobic processing of poultry manure as well as co-digestion studies of chicken manures and organic waste for biogas production.

Substrate/Proportion of substrates	OLR (kgVS/m^3d)	HRT (d)	Volume of reactor (l)	Temp. (^{o}C)	Y_M or Y_B	FA or NH_4^+ or TAN	Pre-treatment	Reference
CS:CM 100:0, 70:30, 50:50, 25:75 10:90[4]	3.19–4.75	21	18	35	Y_M: 0.12[1,2]	FA>1 g/l	no	Callaghan et al. (2002)
CM:AW 7:3[5]	NA	B: 40 d B: 35 d B: 39 d B: 62 d	0.5	35 55 35 55	Y_M: 502[1] Y_M: 506[1] Y_M: 695[1] In: +93% Y_M: 631[1]	FA: 9.7–15.8 g/l	no Ammonia stripped	Abouelenien et al. (2014)
CM:OFMSW 1:0, 0:1, 1:1, 2:1, 3:1, 4:1, 1:2, 1:3 and 1:4[3]	NA	B:15d	automatic methane potential test system	37	Up to 1800 ml[4]	NA	no	Matheri et al. (2017)
CM:CST 1:1.4[3]	4.0	22.5	11	37	Y_M: 223[1]	TAN: 1.6 g/l	no	Li et al. (2014)
CM:CST 1:1[3]	NA	B: 45 d	1	37	Y_M: 328[1]	NA	no	Li et al. (2013)
CM:CST:KW 1:1:1[3]	NA		1	37	Y_M: 420[1]	NA	no	
DM:CM 100:0[5]	NA	B: 30 d	1	35	Y_M: 175.8[1]	TAN: 412 mg/l FA: 7 mg/l	no	Wang et al. (2012)
DM:CM 0:100[5]	NA		1	35	Y_M: 125.5[1]	TAN: 932 mg/l FA: 22.4 mg/l	no	
DM:CM 50:50[5]	NA		1	35	Y_M: 147.4[1]	TAN: 412 mg/l FA: 7 mg/l	no	
PL:CD 100:0[5]	NA	B:50 d	2	32	Y_B: 263[1]	NA	no	Miah et al. (2016)
PL:CD 75:25[5]					Y_B: 469[1]			
PL:CD 50:50[5]					Y_B: 419[1]			
PL:PDR 70:30[5]					Y_B: 221[1]			
CM:CSI 20:80, 30:70, 40:60, 60:40, 70:30[5]	NA	BMP assay 21–30 d	2.5	NA	Y_M: up to 356[1]	NA	no	Sadecka et al. (2016)
CM:HT 10:90, 20:80, 30:70, 40:60, 60:40[5]					Y_M: up to 356[1]			
CM:G 5-95, 20:80, 60:40, 70:30, 90:10[5]					Y_M: up to 272[1]			
CM	1.6–2.0	30–52	95 m^3	35	55–74 m^3/d[7]	NA	NA	Sakar et al. (2009)
CM	4% and 1%[6]	29-12 and 30	NA	37	Y_B: 245–372 and 627[1]	NA	NA	
LFHM	11–12 g COD/(ld)	1–2	2 × 2.6 l UASB	35	3.5–3.6 l/d[7]	NA	NA	
PW	2.9 kg COD/(m^3d)	13.2 h	3.5 l UASB	26–34	0.26 m^3 CH_4/kg COD	NA	NA	
BM:CMa	12 000 and 53,500 mg COD/l	27–91	7 × 100 ml	35	180-270 and 223–368 ml/g COD[7]	NA	NA	
PDR:AW	38.49 kg of substrate	40	0.28 m^3	25–29	137.16 l/d[7]	NA	NA	
CM:SPS 4.3:1[8]	1.72–2.78	23–28	16 l	36	Y_M: 120-290[1]	TKN: 2.16–6.56 g/l	poppy straw was shredded	Bayrakdar et al. (2017)
CM1	5.3–6.0	40–84	10 l	40	Y_M: 370[1]	TKN: up to 26.26 g/kg	Stripping, 70 °C, without artificial pH adjustment	Nie et al. (2015)
CM2					Y_M: 240[1]	TKN: up to 41.07 g/kg		
CM3					Y_M: 200[1]	TKN: up to 27.50 g/kg		
CM:WS	1.5–4.5	10	10 l	NA	Y_M: 170-297[1]	TAN: 1.28 g/l FA; 49.9 mg/l	WS -oxidative cleavage with 7.5% H_2O_2	Hassan et al. (2017)

CM – chicken manure, AW – agricultural wastes (coconut waste, cassava waste (root) and coffee grounds), Y_M – methane yield, Y_B – biogas yield; NA – not available, B – batch assay, OFMSW – organic fraction of municipal waste, KW – kitchen waste, CST – corn stover; DM – dairy manure, WS –wheat straw, PL - poultry litter; CD – cow dung, PDR - poultry droppings, BMP-Biochemical Methane Potential, CSI - corn silage; HT – haulms tomatoes, G – grass, LFHM – liquid fraction of hen manure, PW – poultry wastewater, BW – boiler manure, CMa - cattle manure, UASB – up-flow anaerobic sludge blanket, SPS - spent poppy straw, TKN - total Kjeldahl nitrogen, WS - wheat straw.
[1] – m^3/Mg VS; [2] - methane decreased as the organic loading was increased; [3] – on the basis of VS; [4] –the highest biogas production for the ratio of CM to OFMSW of 4:1; [4] - based on wet weights; [5] – v/v; [6] - influent and 2.53% VS concentration, [7] – biogas, [8]- w/w; [9] - were mixed to achieve C/N ratio of 25 and 20 respectively.

Table 11
Selected characteristics of biochars produced from poultry manure in selected temperatures.

Type of biochar	temp. (°C)	pH	ash (%)	C (%)	H (%)	N (%)	S (%)	O (%)	EC (dS/m)	BET (m^2/g)	O/C	H/C	Na (%)	P (%)	K (%)	Ca (%)	CEC (cmol/kg)
Chicken litter (Qi et al., 2017)	550	7.69	46.20	33.70	2.41	3.81	0.40	13.50	1450	6.97	–	–	–	–	–	–	–
Chicken manure (Li et al., 2018)	300	8.00	36.50	39.07	2.95	3.52	–	17.96	–	4.00	0.46	0.076	–	–	–	–	–
	600	9.22	49.99	32.30	0.93	1.86	–	15.42	–	86.67	0.48	0.029	–	–	–	–	–
Poultry litter (Novak et al., 2009)	350	8.70	35.90	46.10	3.70	4.90	0.78	8.60	–	1.10	0.14	0.960	1.88	2.94	–	–	–
	700	10.3	52.04	44.00	0.30	2.80	1.00	<0.01	–	9.00	<0.01	0.080	2.69	4.28	–	–	–
Poultry manure (Bavariani et al., 2019)	200	7.20	–	39.70	5.62	3.53	–	42.3	8.59	–	–	–	–	3.39	1.044	–	58.0
	300	7.30	–	42.40	5.33	3.80	–	39.1	8.96	–	–	–	–	4.13	1.259	–	69.0
	400	9.98	–	47.90	3.40	4.70	–	31.9	15.27	–	–	–	–	5.58	1.716	–	75.0
	500	10.50	–	55.10	1.98	4.50	–	24.5	18.90	–	–	–	–	6.38	1.970	–	86.5
Poultry litter (Song and Guo, 2012)	300	9.5	47.87	37.99	–	4.17	2.69	–	22.80	2.68	–	–	–	2.27	6.930	7.17	51.1
	350	11.5	51.29	37.65	–	3.22	2.88	–	31.00	–	–	–	–	2.40	7.450	7.64	29.2
	400		56.62	36.10	–	2.63	3.11	–		3.94	–	–	–	2.63	8.120	8.34	
	450		58.66	35.22	–	2.22	3.32	–		5.79	–	–	–	2.66	8.570	8.78	
	500		60.58	34.47	–	1.21	3.40	–			–	–	–	2.79	8.790	9.05	
	550		60.65	33.88	–	0.31	3.50	–			–	–	–	2.98	8.970	9.30	
	600		60.78	32.52	–	0.12	3.53	–			–	–	–	3.05	9.150	9.40	
Chicken litter (Srinivasan et al., 2015)	680	10.1	11.16	86.79	1.89	1.30	–	10.76	14.83	6.96	0.12	0.013	–	–	–	–	–

- quantities of poultry manure generated in poultry production are expected to continue to grow,
- poultry manure is a valuable resource as it contains macro- and micronutrients, and thus has a great potential for agricultural applications,
- there is a number of technologies for processing poultry manure into added value products or recovered energy, however still the most common way of processing poultry manure is biological treatment such as composting or anaerobic digestion,
- a complex approach towards poultry manure is required for more efficient closing carbon, nitrogen and phosphorous loops in agriculture,
- despite overwhelming number of reports and studies on composting of poultry manure with various amendments, still the problems related to the excessive emission of ammonia, and thus nitrogen loss, and odors have not been sufficiently solved,
- similarly in case of anaerobic digestion of poultry manure there is a number of challenges to be addressed when it comes to the properties of substrates and the process itself,
- pyrolysis of poultry manure into biochars is the subject of few on-going investigations and still has not been scaled up to operating installations,
- poultry manure can contain a number of contaminants, including antibiotics or pesticides, and thus pose significant threats to soil and living organisms when applied directly to soil or after biological treatment.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Danuta Dróżdż: Conceptualization, Writing - original draft, Writing - review & editing, Visualization. **Katarzyna Wystalska:** Writing - original draft, Resources. **Krystyna Malińska:** Writing - original draft, Writing - review & editing, Project administration. **Anna Grosser:** Writing - original draft, Visualization, Resources. **Anna Grobelak:** Writing - original draft, Resources. **Małgorzata Kacprzak:** Writing - original draft.

Acknowledgment

This review work was performed within the Nutri2Cycle project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No [773682].

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