Jordanian Journal of Engineering and Chemical Industries

Print ISSN: 2616 - 9584 Online ISSN: 2617 - 720X

# Evaluation of Physical and Chemical Properties of Poultry Sludge and its Suitability for Reuse in Agricultural and Non-Agricultural Applications

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**Abstract**

Disposal of poultry sludge is one of the significant challenges facing cities because of very strict requirements for landfilling and the scarcity of space for landfills. Therefore, the present study aimed to evaluate the physical and chemical properties of poultry sludge and its suitability for reuse in agricultural and non-agricultural applications. Three samples were collected from sludge at the wastewater treatment plant of Al-Thuraya slaughterhouse in Al-Mafraq District, Jordan. The physical and biochemical properties of these samples were analyzed. Also, elemental composition and heat value were determined. The results indicated that poultry sludge had a slightly alkaline pH and a totalmoisture content of 20%, and an average total solid of 80%. The dry solid sludge had a volatile solid content of 94.9% and 5.1% of ash. Also, dry sludge had a high protein content (62 %) followed by carbohydrate (20%) and fiber (17%), with fat being around 1%. The significant elements in the sludge were carbon (65.5%) followed by nitrogen (16%), phosphorous (5%), and sulfur (2%). Heavy metal concentrations in dry sludge ranged from 0.01 to 2mg/kg. These heavy metal concentrations were well below the safe limits recommended by legislators for sludge used as a fertilizer. The findings from this study revealed that dry poultry sludge offers a wide range of potential uses as fertilizer, animal feed, and a source of energy. It should be considered a potentially valuable and sustainable resource rather than a waste product.

**Paper type**: Research paper

**Keywords**: Animal feeds, energy recovery, poultry sludge, greenhouse gas, heavy metals, organicfertilizer.

**Citation**: Irshaid F., Al-Harahsheh A., and O., Alnhoud " Evaluation of Physical and Chemical Properties of Poultry Sludge and its Suitability for Reuse in Agricultural and Non-Agricultural Applications", *Jordanian Journal of Engineering and Chemical Industries*, Vol. **4**, No.3, pp:86-95 (2021).

## Introduction

The poultry industry is one of the fastest-growing sectors of meat production in Jordan and worldwide. According to the Jordanian Department of Statistics data, poultry meat production has grown significantly during the past two decades. From 1970 to 2019, it was estimated that poultry production increased from 7,283 tons in early 1970 to 249,646 tons in 2019, representing a 3428% increase from the corresponding period in 1970. Poultry meat consumption has also rapidly increased across the globe. This is because poultry meat has low costs and affordable prices for low-income families in developing countries. Besides, high consumption of poultry meat was shown to be driven by strong consumer demand, rising incomes, and increasing world population (Davis *et al*., 2013; Ferreira *et al*., 2018; Ha, 2018). Therefore, it is projected that growth in poultry meat production will continue to grow faster than other major meat production sectors worldwide.

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Received on August 19, 2021. Accepted on October 14, 2021.

*Jordanian Journal of Engineering and Chemical Industries* (JJECI), Vol.4, No.3, 2021, pp. 86-95.

The poultry industry is still one of the world's largest producers of sludge in food processing industries. Poultry sludge consists of several offal parts that have little or no value to the customers and poultry industries (Hu *et al*., 2018; Adhikari *et al*., 2018). In addition, it contains diluted blood, loose meat, fibers, colloidal particles, undigested food particles, manure, and suspended solids. It also contains several cells of microorganisms, contaminants, numerous natural compounds, their transformation products, and phytotoxic compounds, commercially and synthetic chemical compounds (Yetilmezsoy *et al*., 2011; Adhikari *et al*., 2018; Ozdemir *et al*., 2020). It is anticipated thatthese potentially harmful compounds and microorganisms might enter food and feed chains and thus might pose a significant risk for humans, animals, and the environment. Therefore, proper disposal of the poultry sludge is essential for reducing the release of harmful pollutants to the environment and preventing health risks to humans and wildlife. Reduction or elimination of poultry sludges has remained the main challenge for governments around the world. To reduce or eliminate the poultry sludge, several methods of poultry sludge management have been used and explored worldwide, including conventional landfill, incineration, use as a natural fertilizer, animal feeding, incorporation into ceramic mass for production of ceramic tiles, and energy recovery (Adhikari *et al*., 2018; Ferreira *et al*., 2018). Landfilling sludge is the last sludge management option for minimizing negative environmental effects and partially resolving the problem of an ever-increasing amount of sludge. Landfilling and direct dumping of sludge near waterways, for example, can have a variety of effects on natural water bodies, including the possible leaching of organic pollutants, toxic heavy metals, bio-resistant, recalcitrant, harmful substances, and pathogenic microorganisms from contaminated soil with sludge into groundwater and surface water (Tiruneh *et al*., 2014; Bouring *et al*., 2015; Kominko *et al*., 2018). Unfortunately, landfilling might bring several undesirable factors such as odor generating constituents and most likely pose a risk for ecosystems, human health, and well-being (USEPA, 2013; Lamastra *et al*., 2018). Therefore, substantial public opposition to the disposal of sludge or waste in landfills has grown worldwide. Sludge dumping in landfills is also regarded as wasteful from an economic standpoint, as it is costly to treat. As a result, the struggle with sludge management and treatment will continue to increase worldwide.

It is pertinent to note that sludge of various kinds has fertilizing values. Consequently, sludges have been traditionally applied to agricultural cropland as an organic fertilizer and landscaping due to reduced cost and low technological demands in light of the increasing costs of chemical fertilizer (Ferreira *et al*., 2018; Kominko *et al*., 2018). However, this value is sometimes minimal in magnitudecompared to the sludge's gross mass. Furthermore, utilization of sludge as an organic fertilizer on crop production and plant growth has a range of negative influences on soil quality, including the high levels of oxygen demand, physical clogging of soil by fat accumulation and presence of pathogens, and high content of heavy metals (Kominko *et al*., 2018). On top of it all, the accumulation of these toxic metals and pathogens in plants might have negative health consequences for animals and humans that consumed them (Watkins and Hash, 2013; Latare *et al*., 2014; Rizzardini and Goi, 2014). For these reasons, the utilization of sludge as fertilizers has been restricted in some countries. Therefore, a clear understanding of the physicochemical characteristics of poultry sludge isessential for developing efficient methods of recycling or utilizing these waste by-products.

Furthermore, there has been a sharp increase in oil prices due to high demand for energy, which is anticipated to continue to increase over the next ten years, mainly due to the ongoing urbanization, growth of the world's population, and the high rates of economic growth (EIA, 2021). This will most likely increase debt burdens, putting a heavy burden on the country's economic growth. Along with that, fossil fuels (coal, crude oil, and natural gas) are non-renewable resources, and using these types of fuels for energy has some severe environmental and public health adverse impacts such as emission of CO2 (Allen *et al*., 2018). Therefore, governments, industries, and scientists in all countries are quietly stepping up their efforts to search for cheap and renewable energy sources such as energyrecovery from sludge. Production of energy from sludge and waste has been viewed by many scientists as the best solution for sludge reduction and/or elimination due to bans imposed by the government on landfilling, the shortage of land for landfill sites, increase in energy prices, $CO_2$ emission, and other environment-related problems (Arshad *et al*., 2018; Raaj *et al*., 2020; Mohammad and Ardebili, 2020). Recently, several types of energy recovery applications have been developed to convert sludge from various sources to energy, including pyrolysis, gasification, and hydrothermal liquefaction (Ferreira *et al*., 2018; Oladejo *et al*., 2019; Alnhoud *et al*., 2021).

Data on the physical, chemical, and biological properties of sludge produced in small wastewater treatment plants is usually lacking in Jordan, especially in industrial factories such as poultry processing facilities. All of the poultry slaughterhouse facilities in major cities of Jordan also suffer from poor regulation or management of poultry sludge and experience some problems such as uncontrolled landfills, improper burning, unpleasant odor, and others. In the Al-Mafraq District, a small quantity of poultry sludge has been used by farmers as fertilizer to optimize crop yield. However, most poultry sludge is often spread on lands in the vicinity of the poultry slaughterhouse or close to the lands that can be developed for agriculture or maybe improperly incinerated due to high transport costs of this sludge to designate landfill sites by the local authority. These serious violationsare considered problematic to our local citizens and government, and they are issues of a global publichealth concern. Furthermore, because global demand for poultry is expected to continue to rise, production of poultry sludge will consequently increase. At the end of this tremendous increase, proper sludge management strategies are critical to reducing the adverse environmental effects of improper handling, usage, and/or disposal procedures. For these reasons, this present study was intended to determine the physical and chemical properties of discharged poultry sludge obtained from the wastewater treatment plant of Al-Thuraya slaughterhouse in Al-Mafraq District, Jordan, and to determine its potential use as soil fertilizer in agriculture, non-agriculture purposes such as animal feed and production of energy.

## 1 Materials and Methods

### 1.1 Study location

The plant of Al-Thuraya slaughterhouse was selected for this study. This facility is a privately owned subsidiary of Al Jazeera Agricultural Company and is located in Al-Mafraq in Jordan. Al-Thuraya is about 70km to the northeast of Amman. The project is located on more than 211,000m$^2$, making it an integrated village with its divisions. The facility contains a small industrial wastewater treatment plant which is mainly used to treat industrial wastewater resulting from various washing operations during the production stages.

### 1.2 Sample collection and preparation

The poultry sludge samples were collected from the wastewater treatment plant of Al-Thuraya poultry slaughterhouse in Al-Mafraq District, Jordan. Three grab samples in the volume of 400mL were collected from sludge coming off a belt filter press using a 500mL glass beaker and a stainless-steel trowel. These samples were collected 30 minutes apart at the same location and were placed in a stainless-steel bucket. Each sample was thoroughly mixed inside the stainless-steel bucket with a stainless-steel trowel to produce a homogeneous sample. All samples were immediately put in a Styrofoam box containing dry ice with a temperature between 0 and 4Cº. After the collection step, samples were taken immediately to the laboratory and kept in a refrigerator at 3$^o$C before use. For physical and chemical analyses, sludge samples were prepared according to the Standard Methods for examining Water and Wastewater (APHA, 2017).

### 1.3 Determination of sludge physical properties

Conventional parameters such as total solids and volatile solids of poultry sludge samples were measured according to the standard methods APHA-2540B, and APHA-2540D, respectively (APHA, 2017). The chemical oxygen demand (COD) and biological oxygen demand (BOD) were also measured using the APHA-5220B, and APHA-5210B standard methods (APHA, 2017). The data for total solids were expressed as a percentage of the wet weight of the sludge sample. Also, the data of volatile solids were expressed as a percentage of the total solids. All the experimental analyses were performed in triplicate. A pH meter (Schott CG 840, Netherland) was used to determine the pH of the sludge water suspension at a 1:2.5 sludge: solution (w/v) ratio. Moisture content for each sample was estimated by a rapid microwave drying method of 985.14 (AOAC, 2000). Ash content was also measured using the methods of 923.03 (APHA, 2017). The ash content represents the total amount of minerals present within a sample of dry sludge. All samples were measured in triplicate.

### 1.4 Determination of protein, carbohydrate, lipid, and fiber contents of poultry sludge

The sludge samples were analyzed for protein, lipid, and fiber, which were measured by the methods of 990.03, 920.39, and 962.09, respectively (APHA, 2017). Carbohydrate content was estimated according to the method described previously (James, 1995). Protein, lipid, fiber, and carbohydrate contents were reported as a percentage of the original sample (% dry matter). All experimental analyses were performed in triplicate, and the resulting values averaged.

### 1.5 Elemental analysis of poultry sludge

The concentrations of major elements, including carbon (C), total nitrogen (N), phosphorus content (P), sodium (Na), potassium (K), calcium (Ca), and sulfur (S), were measured following the standard methods (APHA, 2017). Samples were oven-dried at 60$^o$C until they reached a constant weight for heavy metal content and micronutrient analyses. All of the samples were then crushed in a sludge mill and sieved through a 0.250-mm sieve. The concentrations of cadmium (Cd), copper (Cu), lead (Pb), magnesium (Mg), nickel (Ni), iron (Fe), manganese (Mn), and zinc (Zn) were assessed according to the APHA standard method (APHA, 2017). All experimental assays were carried out in triplicate.

### 1.6 Measurement of heat value

To evaluate the energy yield, poultry sludge samples were milled into 1 mm and oven-dried at 60$^{o}$C for 24 h and then at 105$^{o}$C (Zema *et al*., 2013). Triplicate samples of sludge were randomly selected from stainless steel buckets to determine this sludge's calorific value (CV). Following the determination of wet weight, the CV (HHV: MJ/kg) was measured for each sample directly on a 1-g pill in an oxygen bomb calorimeter (SDM, SN 3472) at the reference temperature (25$^{o}$C). This analysiswas carried out in Natural Resources Authority Laboratory in Amman, Jordan. The calorific value of sludge is the quantity of heat produced by combustion at constant pressure and under "normal" conditions (i.e., 0$^{o}$C and under a pressure of 1,013 millibars).

## 2 Results and Discussion

### 2.1 The physicochemical properties of the poultry sludge

In this study, poultry sludge samples were recovered from the waste treatment plant of Al-Thuraya poultry slaughterhouse in Al-Mafraq District of Jordan and then subjected to physicochemical analysis. **Table 1** presents the results for some physical characteristics of the investigated poultry sludge samples, which indicated that poultry sludge had a slightly alkaline pH of 7.6, an average total solid of 80%, and a total moisture content of 20% at the time of collection. The total solids contained about 5.1% ash and 94.9% total volatile solids content. These values differ from those reported in previous studies (Ferreira *et al*., 2018; Nicoline *et al*., 1995; Dede *et al*., 2017; Ozdemir *et al*., 2020). Variations in sludge compositions and characteristics can be explained by differences in poultry strain/species, diet, slaughtering process and age of animals, type and number of animals slaughtered, and cleaning process deployed at the plant.

The investigated poultry sludge was also analyzed for biochemical properties, including protein, carbohydrate, lipid, and fiber. **Figure 1** shows the proteins, carbohydrates, lipid, and fiber contents from poultry sludge samples. Protein was the most abundant constituent in the sludge samples, accounting for approximately 62.5% of the dry weight of the sludge. Carbohydrate was the second most prevalent constituent of the sludge, accounting for about 20% of the dry weight of the sludge, followed by fiber, which accounted for about 17% of the dry weight and fat, which accounted for less than 1% of the dry weight of the sludge. These findings from the current research are in agreement with previous studies, which indicate that poultry sludge contents have a high concentration of organic matter from soluble proteins, carbohydrates, and fiber (Nicoline *et al*., 1995; Ghaly and MacDonald, 2012; Hu *et al*., 2017). The fiber in sludge is often obtained from plant-based elements removed from the gizzard and gastrointestinal system of birds during the slaughter process. The fiber is mainly composed of nondigestible polymers of complex carbohydrates, including cellulose, hemicelluloses, pectin, and lignin (BeMiller and Whistler, 1996). Recent studies of chemical composition and nutritional values of different sludges revealed that sludge is a good source of proteins, carbohydrates and minerals that could be used in animal feed and pet food (Ghaly and MacDonald, 2012; Hu *et al*., 2017; Adhikari *et al*., 2018).

In general, there is a growing interest worldwide in the utilization of sludges from various sources as an organic fertilizer to minimize environmental and health concerns (Haynes *et al*., 2009; Dede *et al*., 2017; Lamastra *et al*., 2018; Ferreira *et al*., 2018; Alnhoud *et al*., 2021). Although poultry wastes have not been extensively examined as a natural fertilizer source, the available data on biomass yields from other sludge sources is not encouraging. For instance, it has been documented that sewage sludge has a low fertilizer value, and its contribution to soil organic matter is minimal (Krogstad *et al*., 2015). Based on the physical analysis results, the major characteristic of the sludge was a high volatile solid (94.1), which indicated a high fraction of organics in the poultry sludge. In addition, the sludge had sufficient organic biological nutrients (from soluble proteins, carbohydrates, and fiber), adequate alkalinity, and low ash content. The total volatile solids of sludge are referred to as dry organic matter and are often used to characterize the sludge or waste for nutrient recovery. The poultry sludge contains high amounts of organic matter and nutrients. In support of this, previous and recent studies have found that the organic matter of poultry sludge was nutritious and hence can contribute significantly to organisms living in the soil, such as earthworms and microorganisms (Nicoline *et al*., 1995; Dede *et*

**Table 1** Physical properties of experimental poultry sludge.

| Parameter | Value |
|---|---|
| pH | 7.6± 0.2 |
| Moisture content (%) | 20 ±1.3 |
| Total solids (%) | 80±4.3 |
| Total volatile solids (%) | 94.9±5.5 |
| Ash (%) | 5.1±0.8 |
| C/N ratio | 4.1 |
| BOD (mg/Kg) | 2424±24.1 |
| COD (mg/Kg) | 3700±94.1 |

*al*., 2018; Ozdemir *et al*., 2020). Besides, they reported that organic matter usually returns to the soil and goes through the decomposition process and, thus, can influence both the chemical and physical properties of soils. The addition of organic matter can improve the capacity of soil to retain or hold water by promoting soil aggregation and porosity. It was also observed that high volatile solids content led to enhance degradation of organic matter and mineralization of nutrients in wastes or sludges (Haynes *et al*., 2009; Marschner, 2012). Total solids and moisture content are expressed as a percentage of the wet weight of the sludge sample. Volatile solids and ash were expressed as a percentage of the total solids.

Proteins, carbohydrates, lipids, and nucleic acids are the primary components of all living creatures. Therefore, concentrations of proteins, carbohydrates, and fiber are vital parameters for the evaluation of the quality of sludge as animal feed. According to a previous study, poultry sludge was used as a feed constituent for broiler chickens and pigs (Nicoline *et al*., 1995; Ghaly and MacDonald, 2012; Ozdemir *et al*., 2020). The authors reported that the use of poultry sludge as a dietary supplement showed no detrimental effect on the growth in the test animals. They concluded that feeding poultry waste to these animals reduces the cost of feed and the environmental impact in places where extensive poultry farming is practiced. In addition, it has also been reported that high levels of protein level improve the average daily gain for growing cattle and increase the mucosal thickness and the growth performance and feed efficiency (Cui *et al*., 2019). The result from the current study indicated that poultry sludge contains a high amount of proteins (62%). Thus, this result implies that the poultry sludge used in this study has great potential as a dietary supplement or alternative animal feed. It can be used to feed different kinds of animals such as cattle, birds, dogs, cats, fish, and others. However, due to the concerns about the spread of infectious diseases by pathogens such as bacteria, viruses, fungi, or parasites, converting animal sludges or wastes to animal feed is prohibited in many countries. Therefore, further studies are needed to evaluate the safety and digestibility of this poultry sludge in animals.

### 2.2 The elemental composition of poultry sludge

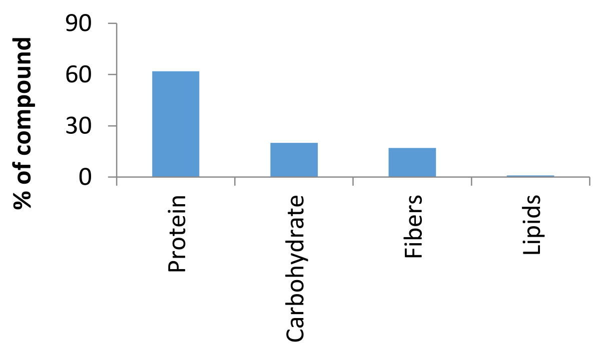


**Fig. 1** Percentage of proteins, carbohydrates and lipids in dry sludge samples obtained from poultry slaughterhouse wastewater treatment plant in Jordan.

Carbon, nitrogen, and phosphorus represent the major chemical elements of many plant fertilizers (Feinerman *et al*., 2004; Haynes *et al*., 2009; Marschner, 2012; Krogstad *et al*., 2015, Delin, 2015). Determination of the concentrations of these elements in poultry sludge samples is vital for evaluating its suitability as a potential plant nutrient source and reducing the use of mineral fertilizer. The results of the chemical analysis of this poultry sludge demonstrated that the structure of the sludge consists mainly of carbon atoms (65%). Furthermore, nitrogen accounts for 16 % of the primary components in dry sludge, with phosphorus (5%) and sulfur (2%) following closely behind (**Figure 2**). This explains the results of the sludge's biochemical examination, which revealed that proteins, carbohydrates, and fiber are the primary constituents in the sludge. In this regard, the results obtained from this research agrees with previous studies, which found that the dry matter of sludge contains mainly macronutrients in the form of bound C, N, and P (Nicoline *et al*., 1995; Ghaly and MacDonald, 2012; Delin, 2015, Dede *et al*., 2017). Macro elements such as carbon, nitrogen, sulfur, phosphorus, and potassium are usually necessary elements in many of the biological processes of all living organisms, including plants. Carbon is a vital element because it is the major component of the four macromolecules in living cells, including proteins, lipids, nucleic acids, and carbohydrates. Nitrogen is also one of the essential elements for the survival of all living organisms because it is required for the synthesis of proteins, DNA, and many biomolecules, including chlorophyll (Haynes *et al*., 2009; Marschner, 2012; Mo *et al*., 2019). Analysis of macroelements in this poultry sludge also revealed that Ca, Mg, K, and Na concentrations were 3.91, 2.11, 1.46 and 0.68mg/kg, respectively, as presented in **Table 2**. The main ingredients in artificial fertilizers used in agriculture are phosphorus, nitrogen, and potassium (Haynes *et al*., 2009; Mo *et al*., 2019). As a result, these inorganic macronutrients are regarded as fertilizer source materials, and their presence in sludges has long been utilized as a barometer of sludge fertilizing value. Recent studies also revealed that the presence of a considerable amount of inorganic macronutrients in organic fertilizers such as nitrogen, phosphorus, sulfur, mineral elements (magnesium, calcium), alkaline metals (sodium and potassium), has been attributed to the improvement of soil physical and chemical properties and stimulate soil microbial activity (Dede *et al*.,2017; Ferreira *et al*., 2018; Ozdemir *et al*., 2020).

Based on previous literature reviews, using sludge as fertilizer is a far better option than burning it in massive incinerators or sending it to landfills (Feinerman *et al*., 2004; Marschner, 2012; Chatterjee *et al*., 2017; Mo *et al*., 2019). According to these studies, the reuse of sludges in non-food biomass crops was regarded as the best management strategy worldwide to minimize environmental and health concerns about sludges. Asa result of the findings from this study, this sludge can be used as a great source of organic matter and inorganic macronutrients and a potential natural fertilizer and/or soil amendment to enhance plant growth and agricultural yields. Moreover, the use of poultry sludge may also replace the use of mineral fertilizers, resulting in a free or low-cost fertilizer. One of the most serious problems in sludge is its heavy metal contents. To guarantee and ensure sludge safety as an organic fertilizer, it is important to measure its heavy metal contents. The concentrations of some selected heavy metals in dried poultry sludge (Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn) are listed in Table 2. The concentrations of Cd, Cr, Cu, Fe, Pb, Mn, Ni, and Zn were 0.01, 0.11, 0.08, 2.0, 0.15, 0.03, 0.09, and 0.33mg/kg, respectively. The concentrations of heavy metals in the present study were closely similar to those commonly found in the previous investigations (Ghaly and MacDonald, 2012; Tytła *et al*., 2016; Dede *et al*., 2017; Ozdemir *et al*., 2020). Previous studies consistently reported that frequent application of sludges in the soil might increase the heavy metal levels in the soil to toxic levels, limiting their usefulness as organic fertilizers (Tiruneh *et al*., 2014; Bourioug *et al*., 2015; Hamnér *et al*., 2015). They opined that high levels of heavy metals affect soil microorganisms, such as nitrogen-fixing bacteria and various biological processes, as well as reducingthe size of the soil microbial biomass. Because of the sludge's toxicity, many countries developed and issued national regulations and policies on agricultural use of sludge as an organic fertilizer. They also reduced the permissible levels of heavy metal contents in sludge to ensure their accumulation in agricultural soils is below any levels that can adversely affect plant growth and crop yield, as well as animals and humans that consumed them (Tytła *et al*., 2016; Ali *et al*., 2019). The concentrations of the heavy metals of sludge used in this study appear to be lesser than the specified limit values that legislators proposed as safe levels for fertilizer products (Saveyn and Eder, 2014). The test poultry sludge meets the requirements for usage as an animal feed, organic fertilizer, or soil improver, based on the chemical composition and safety characteristics analyzed. Nonetheless, more research is needed to understand at what level poultry sludge becomes toxic to plants and agricultural animals and determine any major side effects.

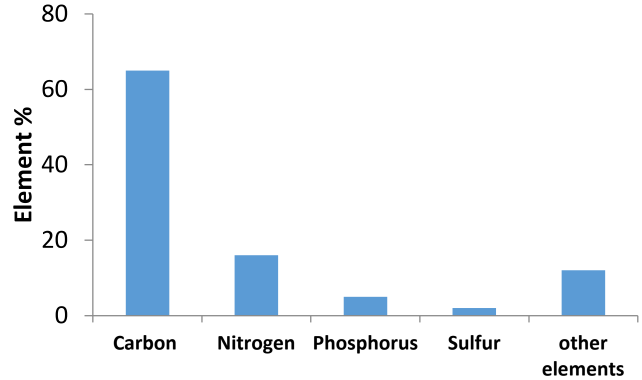


**Fig. 2** Percentage of major elements in dry sludge obtained from poultry slaughterhouse wastewatertreatment plant in Jordan.

**Table 2** The concentration of some selected chemical elements and heavy metals in sludge obtained from poultry slaughterhouse wastewater treatment plant in Al-Mafraq District, Jordan.

| Element | | Concentration (mg/Kg DW*) | Reference value** (mg/ Kg DW) |
|---|---|---|---|
| Calcium | (Ca) | 3.91 | -- |
| Magnesium | (Mg) | 2.11 | -- |
| Potassium | (K) | 1.46 | -- |
| Sodium | (Na) | 0.68 | -- |
| Cadmium | (Cd) | 0.01 | 1.5 |
| Chromium | (Cr) | 0.11 | 100 |
| Copper | (Cu) | 0.08 | 200 |
| Iron | (Fe) | 2.00 | 149 |
| Lead | (Pb) | 0.15 | 120 |
| Manganese | (Mn) | 0.03 | 108 |
| Nickel | (Ni) | 0.09 | 50 |
| Zinc | (Zn) | 0.33 | 200 |

*DW: dry weight of sludge. ** The proposed limit values for compost (Saveyn and Eder, 2014)

### 2.3 Determination of the calorific values of poultry sludge

Due to the massive increase in waste and sludge production across the globe, it is still difficultto reduce or eliminate sludge alone via utilizing the conventional methods of sludge disposable such as landfilling, incineration, and agricultural use such as fertilizer. It is a fact that a large amount of energy in the world is derived from non-renewable sources such as oil, coal, and gas.

Moreover, only a small percentage of global energy (13%) is usually generated from renewable sources such as sludges and others (Oladejo *et al*., 2019; EIA, 2021). According to many previous studies, the recovery of energy from raw solid organic wastes or sludges seems to be the best choice or solution for sludge management compared with conventional methods (Arshad *et al*., 2018; Raaj *et al*., 2020; Mohammad and Ardebili, 2020). In this study, the calorific value for this poultry sludge was measured and compared to the calorific values of conventional fossil fuels and some alternative biobased fuels (**Table 3**). Based on the measured heat value for the poultry slugged sample, it is clear that this dry sludge contains a calorific value of about 17,000kJ/kg. This value was compared to other combustible materials and was very close to well-known materials such as wood and natural coal.

Similarly, in terms of energy content, previous studies indicated that the higher calorific value of dried sludges of various kinds was found to be approximately between 8000 and 1800kJ/kg for dry matter (Arshad *et al*., 2018; Ferreira *et al*., 2018; Đurđevi´c *et al*., 2019; Ozdemir *et al*., 2020). These studies also reported that the calorific value and the properties of the sludges often provide valuable information on the utility of the sludge for either composting or for biogas production as fuel via biological conversion. They also revealed that the amount of energy recovery depends on both the type of tested sludge and moisture content as well as the total carbon content of the sludge. Both moisture and ash are considered undesirable components in sludge as they add more weight to the fuel without adding to the heating value and hence represent the non-combustible components of the sludge waste. These parameters are essential in the context of the potential incineration of sludge as fuel. The examined sludge in this study had high contents of total solids and low total moisture content and ash. These parameters demonstrated that energy recovery from poultry sludge would be the most beneficial option for poultry sludge management.

**Table 3**. Heat value for poultry sludge and heat values of various fossil fuels as well as some alternative biobased fuels.

| Fuel | Higher Calorific Value (kJ/kg) |
|---|---|
| Poultry Sludge | 17,300 |
| Bituminous coal | 17,000-23,250 |
| Butane | 49,510 |
| Charcoal | 29,600 |
| Coal | 15,000-27,000 |
| Coke | 28,000-31,000 |
| Diesel | 44,800 |
| Ethanol | 29,700 |
| Gasoline | 47,300 |
| Lignite | 16,300 |
| Peat | 13,800-20,500 |
| Wood (dry) | 14,400-17,400 |
| Natural gas | 43,000 |
| Propane C3H8 | 101,000 |
| Gas oil | 38,000 |
| Heavy fuel oil | 41,200 |
| Kerosene | 35,000 |

As mentioned above, the present study revealed that the test dry poultry sludge had high volatile solids (94.1 %) and low heavy metal contents, and its pH was slightly alkaline. The quality and applicability of sludge from various sources for energy production are characterized by their physicochemical features, and the factors that may influence them (Arshad *et al*., 2018; Ferreira *et al*.,2018; Đurđevi´c *et al*., 2019; Ozdemir *et al*., 2020; Raaj *et al*., 2020; Mohammad and Ardebili, 2020). Also, the same studies discovered that a high volatile solid content, low moisture level, and a more significant alkaline state could all help anaerobic digestion produce biogas. Sludge with less than 60% organic matter contributes little to biogas production. According to these studies, the recommended total volatile solid range of sludge for biogas production is 70 to 95% of the total solid.

Additionally, the findings from this study add to the growing body of evidence that sludge with high volatile solids and low heavy metals can be used for both energy recovery and nutrient recovery. High energy consumption from non-renewable sources such as natural gas, hard coal, and fuel oil is linked to greenhouse gas emissions in industrialized and developing countries. Therefore, greenhouse gas emissions contribute significantly to global warming and air pollution. These climate changes can have permanent negative impacts on all living organisms. For this reason, controlling emissions of greenhouse gases is considered a global problem that requires a global solution, and efforts should be made to keep the concentrations of these contaminants at levels safe for humans and aquatic organisms (Allen, 2018; EIA, 2021). In terms of greenhouse gas emissions, it was demonstrated that dried sewage sludge emits fewer greenhouse gases than natural gas, hard coal, and fuel oil by incineration (Đurđevi´c *et al*., 2019). Most recently, besides the positive impact on the economy, biogas production and nutrient recovery from sludge can reduce both greenhouse gas emissions and the use of mineral fertilizers (Oladejo *et al*., 2019). As mentioned earlier, the average generation rate of poultry sludge is 500kg/day at Al-Thuraya poultry slaughterhouse in Al-Mafraq District; the amount of sludge generated yearly is calculated as 182.5 tons per year. According to the amount of generated poultry sludge per year at this facility, the total amount of energy generated by the complete combustion of this sludge is approximately $3103x10^6$ kJ/kg per year. Therefore, based on the physical and chemical parameters of this poultry sludge and in the light of these data, it is reasonable to conclude that this sludge can be a good choice as a renewable energy source for electricity production when compared to natural gas, hard coal, and oil (Ferreira *et al*., 2018; Đurđevi´c *et al*., 2019). In addition to economic advantage, energy generation from poultry sludge would have environmental benefits such as reducing sludge volume and mass, followed by reducing unpleasant odours and greenhouse gas emissions and eliminating other environmental pollutions. In agreement with the findings made from this study, many recent investigations demonstrated that sludge energy could be utilized as usable heat, electricity, or converted back to fuel through a variety of processes, including combustion, gasification, pyrolization, anaerobic digestion, and landfill gas recovery (Arshad *et al*., 2018; Đurđevi´c *et al*., 20191, Oladejo *et al*., 2019; Raaj *et al*., 2020). These studies also suggested that biogas generation derived from different types of wastes or sludges in various countries is practically possible, economically feasible, and environmentally friendly.

Finally, it is reasonable to conclude that the physiochemical characteristics of the investigated poultry sludge in this study correlate very well with properties that are most suitable for biogasproduction and nutrient recovery (Maragkaki *et al*., 2018; Piekutin *et al*., 2021). Apart from those mentioned above, this study has some limitations. This is because this study focuses on determining the physical and biochemical properties of sludge collected mainly from a single poultry slaughterhouse in the Al-Mafraq District. First, other heavy metals, such as mercury (Hg), cobalt (Co), molybdenum (Mo), vanadium (V), arsenic (As), beryllium (Be), lithium (Li), and selenium (Se), were not included in the elemental analyses.

These heavy metals are toxic or poisonous at low concentrations and have adverse effects on the environment and human health. Therefore, the presence and activity of heavy metals in poultry sludge are of fundamental importance to the productivity of agricultural soils. Exposure to these dangerous heavy metals can cause damage to every organ in the human body. Second, this investigation did not assess the microbial ecology of the investigated sludge samples. There are growing concerns about the presence of several pathogens (bacteria or viruses) in slaughterhouse poultry sludge that may be capable of infecting animals and can be transmitted from animals to humans, which might cause global pandemics. Identification and characterization of the microbial ecology of poultry sludge can provide more reliable risk assessmentsto guarantee the safety of this sludge as a biofertilizer and/or as feed supplements for animals and help to improve current management strategies to enhance sludge utilization and disposal. Microorganisms commonly influence soil fertility in the soil; therefore, a future study must be carried out to detect microorganisms and assess their abundance, composition, and function within the investigated sludge. The effects of the addition of dried poultry sludge on field soils treated with wastewater obtained from the wastewater treatment plant are currently being explored.

## Conclusions

The findings of this study revealed the presence of significant amounts of organic chemicals and inorganic micronutrient fertilizers in the test sludge and minimal concentrations of heavy metals, suggesting that this poultry waste could be used for many purposes, including biofertilizer, animal feeding, and biofuels. Also, the study indicated that heavy metals were far below the permissible limit values for utilizing poultry sludge for purposes of organic fertilizer and as animal feed. Following the outcomes of physical and chemical analyses of investigated sludge, the suggested disposal methods can be considered as the most suitable options or choices to the conventional methods such as landfills and dumping in nearby rivers. Finally, the adoption of energy generation technology from poultry sludge would be economically beneficial to the Al-Mafraq District. Thus it will be a great start or move towards the promotion of renewable energy sources in the country. Indeed, utilization of these disposal methods can play vital roles in reducing the volume of poultry sludge that goes to landfills, eliminating odor emissions, protecting the environment from hazardous wastes or toxic chemicals, and contributing to a reduction in greenhouse gas emissions.

### Nomenclature

| | | |
|---|---|---|
| APHA | =American Public Health Association | [-] |
| AOAC | =Association of Official Agricultural Chemists | [-] |
| COD | =Chemical Oxygen Demand | [-] |
| CV | =Calorific Value | [kJ/kg] |
| BOD | =Biological Oxygen Demand | [-] |
| DW | =Dry weight | [g] |
| EIA | =Energy Information Administration | [-] |
| HHV | =Higher Heating Value | [-] |
| USEPA | =United States Environmental Protection Agency | [-] |

### Acknowledgments

The authors would like to express their gratitude to the National Program "Faculty for Factory" in Amman, Jordan, for providing financial support for this study. The authors would like to thank the Al-Thuraya Slaughterhouse and Wastewater Treatment Plants staff and managers for their cooperation in obtaining sludge samples. Also, the authors gratefully acknowledge with gratitude to the staff of Natural Resources Authority Laboratory for their assistance, technical support, and cooperation.

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