Turkish Journal of Agriculture - Food Science and Technology, 12(8): 1467-1475, 2024
DOI: https://doi.org/10.24925/turjaf.v12i8.1467-1475.6780

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Pollutant Effects and Management of Animal Manure

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A R T I C L E I N F O

Review Article

Received : 16.03.2024
Accepted : 06.07.2024

Keywords:
Animal manure
Pollution
Manure management
Methane emissions
Livestock waste treatment

A B S T R A C T

Animal manure pollution constitutes a significant environmental issue, particularly in areas with intensive livestock activities. Manure, due to its various pollution loads such as nitrogen, phosphorus, heavy metals, and pathogens, can have adverse effects on soil, water resources, and air quality. Among manure management practices, sustainable methods such as composting, biogas production, and advanced treatment techniques stand out. These methods offer effective solutions for reducing the environmental impact of manure, while also holding the potential to be valued as valuable resources for agriculture and energy production. The growth in the global population along with urbanization has intensified the demand in commerce, industry, and agriculture sectors. This need to satisfy the supply-demand dynamics has led to increased production activities, subsequently giving rise to significant waste management challenges. This review examines the environmental impacts of pollution originating from animal manure, current management strategies, and research developments (R&D) in this field.

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Introduction

The global increase in population along with urbanization has led to intensive production activities in the commerce, industry, and agriculture sectors to meet the supply-demand relations, thereby creating a waste problem. (Kaza et al., 2018). It is estimated that by 2030, approximately 2.59 billion tons of waste will be generated worldwide, with this figure potentially reaching 3.4 billion tons by 2050 and approximately 10.2 billion tons by 2100 (Peng et al., 2023). Especially when compared to other sectors, the agriculture and food industry contributes to a higher amount of both solid and liquid waste due to intensive production systems (Ferreira et al., 2016; Tripathi et al., 2019; Lee et al., 2020). Agricultural wastes are considered organic wastes and are generally classified as secondary products of agricultural enterprises, being labeled as 'waste' because they are not recognized as primary products (Westerman and Bicudo, 2005; Koul et al., 2022). In agricultural enterprises, areas of plant production, fattening areas, animal manures, and crop residues form the main source of solid and liquid wastes (Akinrinmade et al., 2020).

While animals provide essential food sources such as meat, eggs, and dairy products, they also generate significant amounts of animal manure through their digestion and metabolism processes. From a utilization perspective, animal manure is a valuable resource due to its low economic cost, high availability, and wide range of applications (Qi et al., 2023). The composition of animal manure, enriched with functional groups along with macro and micronutrient elements, significantly contributes to the enhancement of soil quality. Consequently, it is extensively favored for applications in soil amendment and plant nutrition, owing to its beneficial impacts on agronomic parameters (Rayne and Aula, 2020). Contrary to beneficial aspects, animal manure may harbor pathogens such as Escherichia coli and Salmonella (Lin et al., 2022), contain heavy metals including iron (Fe), zinc (Zn), cadmium (Cd), and copper (Cu) (Li et al., 2020b), as well as microplastics (Wu et al., 2021a) and antibiotics, notably enrofloxacin and amoxicillin (Zheng et al., 2020; Quaik et al., 2020). These constituents have the potential to contribute to the leaching of soil nutrients, thereby facilitating eutrophication (Giosanu et al., 2022), and to the generation of emissions of toxic gases, including ammonia, methane, and hydrogen sulfide, thereby exacerbating environmental pollution and ecological imbalance (Kupper et al., 2020).

The failure to appropriately process and valorize animal manures is assuming a polluting role in air, water, and soil, thus emerging as a significant global issue (Lin et al., 2018). To prevent or minimize environmental pollution, a multitude of methodologies for the valorization of animal manure waste has been identified in prior research (Paik et al., 1996; Gökmen and Sarıçoban, 2012; Wei et al., 2021; Qi et al., 2023). Among the most commonly employed strategies for the valorization of manure waste are agricultural applications aimed at enhancing the physical, chemical, and biological characteristics of soil (including manure treatment technologies and composting), the generation of energy (comprising heat, liquid fuels, and electricity), and the synthesis of chemical products (such as nitrogen-based compounds and volatile organic acids) (Shen et al., 2015; Mengqi et al., 2021; Awasthi et al., 2022).

This review has been written with the aim of investigating and evaluating the polluting effects of animal manure wastes on the environment and the valorization of waste through methods that minimize pollution levels.

Animal Manure Pollution

According to data from the last 20 years, the global population of farm animals has been on the rise (FAO, 2023). In parallel, an increase in the quantity of manure is anticipated. Animal manure contains organic nutrient groups, inorganic nutrients such as essential elements Nitrogen (N), Phosphorus (P), Potassium (K), and Sulfur (S); secondary nutrients like Magnesium (Mg) and Calcium (Ca), trace elements (Fe, Zn, Mn, Mo, and Cu), and beneficial, pathogen microorganisms, making it a nutrient reserve especially for plant production (Zhong et al., 2012; Kumar et al., 2013; Li et al., 2020b). Furthermore, the increase in greenhouse gases (such as CH_4, N_2O, and CO_2) emitted into the atmosphere from farm animals, the excessive use of heavy metals like Fe, Cu, Zn in feed additives and nutritional supplements in intensive livestock areas, and the increased emergence of resistant microorganisms due to the use of antibiotics for disease prevention, have resulted in the polluting effects of waste manures in the environment (Tasho and Cho, 2016; Guan et al., 2018; Cheng et al., 2022; Danyer, 2023). The composition of animal manure is contingent upon several determinants, including the species of the animal, its dietary, the excretory mechanism, and the agricultural practices employed for rearing (Herrero et al., 2013). The mean volumes of manure produced daily exhibit variability contingent upon the species; bovines yield 10-20 kg, goats and sheep produce 2-3 kg, whereas poultry yields are in the range of 0.08-0.1 kg (Paglari et al., 2020; Khan et al., 2021; Bryant et al., 2022). Notably, manures derived from poultry are recognized for their elevated levels of nitrogen and phosphorus when juxtaposed with manures from other livestock categories (Dróżdż et al., 2020). The mean concentrations of nutrient elements within manures from various livestock species are enumerated in Table 1.

Inadequate management of manure waste within livestock farms precipitates the dispersion of high concentrations of N and P, which act as pollutants to terrestrial and aquatic ecosystems, as well as the atmosphere (Boyacı et al., 2011; Miles et al., 2014; Hollas et al., 2022). It is well-documented that animal manures are rich in N and P, a fact substantiated by multiple research endeavors (Karunanithi et al., 2015; Lemming et al., 2019; Li et al., 2020a). Phosphorus is present in the soil predominantly in forms such as orthophosphates, condensed phosphates (including pyrophosphates, metaphosphates, and polyphosphates), and organic phosphates (Yılmaz et al., 2022). Phosphorus linked to organic matter in animal manure undergoes mineralization by microbial action, accumulating in the soil and, over time, leaching into subterranean and surface water bodies through rainwater infiltration and irrigation, thereby infiltrating rivers and lakes (Wang et al., 2022). Such accumulations of P in aquatic systems catalyze the overgrowth and proliferation of algae and phytoplankton, culminating in eutrophication characterized by an escalated depletion of dissolved oxygen in these water bodies (Wurtsbaugh et al., 2019).

Organic nitrogen in animal manure, in the forms of urea, uric acid, and ammonia (NH_3), integrates into the soil. Organic nitrogen and NH_3 are reduced by microorganisms to nitrite (NO_2) and nitrate (NO_3) salts, of which a portion is retained at the soil surface while another fraction percolates into subterranean and surface waters, resulting in losses. The leakage losses in the form of NO_3 are referred to as 'nitrification.' Excessive NO_3 leakage leads to nitrate contamination in both groundwater and surface waters (Ibrikci et al., 2016; Craswell, 2021). Similarly to P, the leaching of N from the soil stimulates the proliferation of aquatic organisms, increasing oxygen consumption and leading to the demise of these organisms (Zheng et al., 2019). Denitrification bacteria present at the soil surface facilitate the transformation of NH_3, NO_2, and NO_3 salts back into the gaseous form of N, which is then released back into the atmosphere (Guo et al., 2022; Nie et al., 2023). Furthermore, it is recognized that farm manure wastes also emit harmful greenhouse gases to the atmosphere, such as hydrogen sulfide (H_2S), nitrogen dioxide (NO_2), and nitric oxide (NO) (Tanaka et al., 2019; Cao et al., 2023). Nitrogen emissions originate from livestock bedding and storage surfaces (Fangueiro et al., 2008; Singurindy et al., 2009). The contribution of N losses in the form of nitrogen NO_x to global warming is increasingly recognized (Suddick et al., 2013).

Table 1. Nutrient element contents in manures from various animal sources (Dróżdż et al., 2020).

Species of animal	Nitrogen (kg mg^{-1})	Phosphorus (kg mg^{-1})	Potassium (kg mg^{-1})	Calcium (kg mg^{-1})
Sheep	7.5	3.8	11.9	5.8
Chicken	15	15	8	24
Cow	4.7	2.8	6.5	4.3
Duck	8	11	5	13.5
Horse	5.4	2.9	9	4.3

Heavy Metal Contamination from Animal Manure Sources

Heavy metals are known to be introduced into soils through animal manure, particularly because of their incorporation into livestock feed additives (Dai et al., 2016; Gul et al., 2015; Mu et al., 2020). Beyond basic nutritional requirements, livestock are supplemented with minerals containing heavy metals such as Co, Cu, Fe, Mn, Zn, and Cd (López-Alonso, 2012). These essential metals, utilized in mineral nutrition, play critical roles in regulatory, structural, physiological, and catalytic functions within animal systems (Sönmez and Kılıç, 2021; Suttle, 2022).

In the investigation conducted by Luo et al. (2009), the presence of Zn, Cu, Pb, and Cr was detected in cattle manure. Additionally, Sungur et al. (2016), in their study aimed at assessing the heavy metal concentrations in various animal manures, determined that among cow, chicken, and goat manures, the sequence of metal abundance was Mn and Zn> Cu, Cr, and Ni > Cd, Pb, and Co, with chicken and cow manures exhibiting higher levels of Cd, Mn, and Zn, while goat manure was found to contain higher concentrations of Co, Mn, and Cd. Overall, the Zn and Cu content in animal manures is notably high, with poultry manures being identified as having elevated concentrations of these metals (Zhang et al., 2012; Guan et al., 2018; Qian et al., 2018). The reason for this situation is that the feed contents in poultry farming contain higher levels of Zn and Cu compared to other animal feeds (Liu et al., 2020). Additionally, Zn and Mn in animal manure are generally mobile in soil, whereas Cu, Pb (Nomeda et al., 2008), Cr and Ni is found in immobile fractions (Lu et al., 2014; Sungur et al., 2016). Heavy metals in animal manure, along with environmental components, enter the food chain, where the accumulated heavy metals in food webs can exhibit toxic, carcinogenic, and lethal characteristics on living organisms (Duruibe et al., 2007; Engwa et al., 2019).

Microplastic Contamination Originating from Animal Fertilizers

Microplastics are generally defined as plastic particles smaller than 5 mm in size (Hartmann et al., 2019). They accumulate in soil, water, and air due to both natural and anthropogenic factors, transferring to organisms and their wastes (Yin et al., 2023). Among the types of microplastics found in soil and water sources are polyethylene, polyvinyl chloride, polypropylene, polystyrene, polyamide and polyethylene terephthalate (Zhu et al., 2019). Microplastics enter the environment through sources such as feed bags, water containers, feed storage areas, and coatings of nutritional products in the cultivation of farm and poultry animals (Wu et al., 2021b). The flow cycle of microplastics in animals is illustrated in Figure 1.

Beriot et al. (2021) collected samples from the soils of sheep grazing areas and their manure, reporting the presence of microplastics upon analysis. Similarly, there are studies supporting the presence of microplastics in sheep and goat manure (Omidi et al., 2012; Ngoshe, 2012; Otsyina et al., 2018; Mekuanint et al., 2017). Furthermore, Lwanga et al. (2017) detected microplastics in the digestive systems of poultry and their manure. Additionally, Yan et al. (2020) reported the identification of polyethylene terephthalate, a type of microplastic, in chicken manure during their research on microplastics in various types of animal waste.

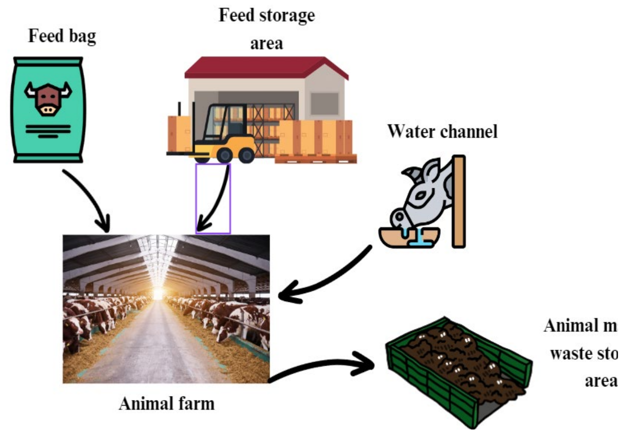

Figure 1. The cycle of microplastic transfer in animals

Antibiotic Contamination Originating from Animal Fertilizers

In the realm of animal husbandry, antibiotics are utilized to enhance growth rates and manage diseases, leading to their integration into the soil via the direct application of animal manures (Tasho and Cho, 2016). It was projected that around 63,151 tons of antibiotics were administered to livestock in 2010, with forecasts indicating a surge by approximately 67% by the year 2030 (Van Boeckel et al., 2015). Predominantly, the antibiotic classes employed are tetracyclines, sulfonamides, and macrolides in descending order of usage (Kim et al., 2011). The adsorption properties of certain antibiotics, particularly sulfonamides and fluoroquinolones, towards organic matter are notably robust (Sarmah et al., 2006); (Hong et al., 2023). The quantity, composition, and treatment duration of antibiotics used in livestock significantly influence their assimilation into the soil, varying with the type of animal species involved (Zuccato et al., 2001). When examined in terms of animal type, the amounts of residues in manure waste have been determined through various studies to be in the order of chicken > pig > cow (Zhang et al., 2008; Zhao et al., 2010). The persistence of antibiotics in the environment varies depending on soil type, manure pH, ambient temperature, and light exposure (Grenni et al., 2018). Seyoum et al. (2021) reported in their study on antibiotic content in sandy, loamy-sand, and clay soils that an increase in clay content enhanced antibiotic retention. Furthermore, Li et al. (2011) found in their study that the decrease in pH caused by the soil's organic matter was statistically positively correlated with the concentrations of sulfonamides and tetracyclines, with R values of 0.86 and 0.93 respectively, which is supported by the findings of Conde-Cid et al. (2020) that there are positive relationships between pH and antibiotics. Contrary to these findings, Ok et al. (2011) did not identify a correlation between antibiotic content and the chemical properties of soil in their study. Soil is recognized as a critical component of environmental resilience, serving as a reservoir for both antibiotics and antibiotic resistance genes. Soil bacteria can acquire resistance from exogenous sources through the addition of antibiotic resistance genes from animal manure wastes to agricultural soils via the process of horizontal gene transfer (Xie et al., 2018). The emergence of resistant pathogens leads to an increase in the prevalence of various diseases and a corresponding rise in treatment costs (Forsberg et al., 2012).

Strategies for the Management and Utilization of Animal Manure

Environmental issues caused by animal-derived manure wastes have a global impact, necessitating the management of livestock production systems and related wastes through more sustainable processes (Tullo et al., 2019). The concept of sustainability in livestock and agricultural activities implies maintaining production levels within the capacity of the ecosystem that supports these production activities (Duru and Therond, 2015). To mitigate the contributions of livestock to climate change, scholars such as Kaufmann (2015) and Herrero et al. (2016) have articulated the necessity for the adoption of strategies aimed at enhancing production efficacy and animal health, alongside the deployment of manure management practices conducive to the reclamation of the main energy and nutritional constituents contained within animal manure wastes. The strategic management of animal manure wastes is fundamentally predicated upon the utilization of technologies pertaining to feed, energy, and fertilization.

Antibiotic Contamination Originating from Animal Fertilizers

Animal manure wastes are comprised of crude fat, undigested crude protein, an assortment of vitamins, minerals, and carbohydrates (Pandey et al., 2014). Consequently, they are being repurposed as feed, necessitating the implementation of disinfection, sterilization and elimination procedures for their utilization and valorization as feed products (Qi et al., 2023). Notably, the manure wastes of poultry species, such as chickens, are utilized as feed in ruminant nutrition due to their uric acid content (Wang et al., 2021). The utilization of single-cell protein from poultry manure as feed represents an innovative approach (Sharif et al., 2021). When chicken manure is used as feed additivies, it is known to possess an energy value of 2000 kcal g^{-1} in the nutrition of sheep and cattle (Demirulus and Aydın, 1996; Eleroğlu et al., 2013). Katili et al. (2021) in their study on the use of chicken manure as animal feed through microbial technologies, indicated its potential for effective use and cost reduction. Additionally, Nisa and Rosariastuti (2022) suggested that the use of chicken manure waste as feed in fish farms could enhance production. In research on vermicomposting, Bellitürk (2016) found that manure wastes from various animals such as horses, rabbits, cattle, and chickens, when combined with organic wastes like forest litter and pruning residues and fed to worms, positively contributed to the enrichment of nutrient content when used in feed technology. However, the presence of toxic components such as pathogens, antibiotic residues, heavy metals, and microplastics in these materials poses negative implications for their potential use in feed technology (Li et al., 2019).

Application of Animal Manures for Energy Production

With the increasing demand for energy and the depletion of fossil resources, animal manure wastes have become a potential source of energy (Choi et al., 2014). Methanogen bacteria found in animal feces cause CH_4 (methane) emissions, accounting for about four percent of other methane sources (Tauseef et al., 2013). The anaerobic fermentation process is considered a preferred method for biogas production with the aim of minimizing harmful gas emissions (Zhang et al., 2014; Fuchs et al., 2018). Biogas is defined as a form of renewable energy produced through the decomposition of various organic materials during the anaerobic fermentation process (Mao et al., 2015; Zamri et al., 2021). The composition of biogas primarily consists of methane and carbon dioxide, with other gases such as nitrogen, hydrogen, hydrogen sulfide, ammonia, and water vapor present in smaller quantities (Prato-Garcia et al., 2023). The content of biogas is presented in Table 2.

The production of biogas occurs through a three-stage process comprising hydrolysis, acidogenesis (fermentation), and methanogenesis, facilitated by the activities of various microorganisms (Najafpour, 2015; Neshat et al., 2017). The stages of biogas production are presented in Figure 2.

The biogas production process entails a multi-stage biochemical transformation that includes the conversion of complex organic molecules into methane through microbial activity. In the initial stage, particulate organic compounds such as cellulose, fats, starches, and proteins are broken down by hydrolytic enzymes into smaller, water-soluble monomers like amino acids, long-chain fatty acids, and monosaccharides. These enzymes are secreted by anaerobic and facultative anaerobic microorganisms, and this transformation process is called hydrolysis. The monomers obtained after hydrolysis are converted into short-chain volatile fatty acids such as lactic acid, propionic acid, butyric acid, and valeric acid through microbial activities, creating an acidic pH environment. In the second stage, acetogenesis, acetogenic microorganisms utilize the short-chain volatile fatty acids produced in the first stage to generate acetic acid, carbon dioxide (CO_2), and hydrogen (H_2). Methanogenesis is the final and critical stage of biogas production. Methanogenic archaea synthesize methane gas (CH_4) under anaerobic conditions using acetic acid and H_2-CO_2 (Tauseef et al., 2013; Kafle and Chen, 2016).

Table 2. Concentrations of various gases in biogas composition (Baredar et al., 2020).

Gases contained	Symbols	Volumetric ratios (%)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapor	H_2O	2-7
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Sulfide	H_2S	20-20000 ppm

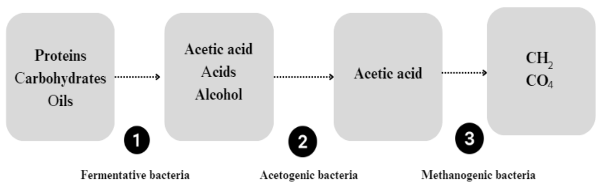

Figure 2. Stages of biogas production

Table 3. CH_4 ratios and biogas production capacities of animal manure wastes

Types of animal manure	CH_4 volume content (m^3 kg^{-1})	Biogas production (m^3 kg^{-1})	Reference
Sheep manure	0.1	0.22-0.24	(Li et al., 2020c); (Wang et al., 2023)
Cattle manure	0.14	0.26–0.28	(Li et al., 2020c); (Wang et al., 2023)
Chicken manure	0.27	0.4-0.6	(Noorollahi et al., 2015)

This process forms the basis of biogas production and leads to the production of methane, carbon dioxide, and trace amounts of other gases. The conversion of organic waste into energy is a critical multi-stage process that enables the sustainable production of renewable energy sources (Nguyen et al., 2019; Li et al., 2020c). According to Xueqing et al. (2011), one cubic meter of biogas can produce approximately 23.4 kilojoules (kJ) of thermal energy, which is equivalent to the energy released by the complete oxidation of 0.55 kilograms of diesel fuel or 0.8 kilograms of coal. *Table 3* provides information on the volume content of CH_4 and biogas production amounts for various animal manures.

Silwadi et al. (2023) calculated the biogas production by anaerobic fermentation of camel, cow, and chicken manure in 1.5 liter bottles and reported that the biogas production increased 28 times by mixing the three types of manure in the same ratio compared to using them separately. Cow, camel, and chicken manure were 64 l kg^{-1}, 43 l kg^{-1} and 55 l kg^{-1} respectively. In addition, they reported that cow manure produced more biogas than the other manures used in the study, followed by camel and chicken manure. They stated that the reason for this situation was that the biogas production of chicken manure stopped 60 days after the start of biogas production. In this case, the biogas production of camel manure was found to be high at day 100. Seglah et al. (2022) reported that the estimated biogas potential of different animal manures was 27.15 million m^3 for cattle and 1.87 million m^3 for chickens. In another study, Ameen et al. (2021) investigated the effect of anaerobic digestion of chicken, pig and cattle manure in 1 liter bottles on biogas yield, adding 1:1:1:1:1, 2:1:1:1:1 and 3:1:1:1:1 ratio and measuring the methane yield at different temperatures (35, 40, 50, 55ºC). At the end of 60 days, they reported that the 1:1:1:1:1 ratio and 40ºC produced higher biogas and methane yields compared to the other mixture ratios and temperatures.

Use of Animal Manure in The Composting Process

Composting is the process of mineralization of organic waste by thermophilic and mesophilic microorganisms under aerobic conditions into inorganic compounds such as carbon dioxide, water and ammonium or stable organic matter such as humus, thereby reducing weed seeds and pathogens and reducing the risk of pollution (Qian et al., 2016). Returning livestock manure to soil in compost form improves soil physical, chemical and biological properties (Sun et al., 2015; Lin et al., 2019). Compost quality is determined by factors such as microorganisms, aeration, C/N ratio, temperature, pH, moisture, particle size and composting time (Gnagwar et al., 2019; Chia et al., 2020). For example, it is recommended that C/N ratio should be 30 because below 30 results in N losses and above this value increases composting time, and pH should be between 6.7-7.5 because initial pH of composting process above 7.5 results in N losses (Chen et al., 2016; Onwosi et al., 2017). The advantages and disadvantages of using animal manure in composting are as follows (Bernal et al., 2009; Koul et al., 2022).

Advantages

- Assurance of microbial stabilisation
- Deodorisation and control
- Reduce fertilizer required and moisture
- Increases the potential for storage, transport and use
- Provides pathogen and weed control

Disadvantages

- Increased need for bulking agents
- Costly to install and maintain
- Large space requirements for operation and storage

Wang et al. (2021) investigated the effects of chicken, cattle and sheep manure as compost raw materials and sawdust for moisture stabilization on the physicochemical properties of compost. They reported that the high total nitrogen of compost in chicken manure was due to the protein feed, in this case sheep and cattle manure compost had a higher C/N ratio than chicken manure. Chen et al (2019) investigated the use of poultry and cattle manure as compost and reported that using microorganisms as carbon and nitrogen sources decreased carbohydrate and protein content, and that poultry compost contained higher protein than cattle compost.

Conclusion

For environmental sustainability and resource efficiency, the management of animal manure is crucial. The review found that the adoption of sustainable manure management techniques offers significant benefits in reducing manure pollution and maintaining environmental quality. Practices like composting and biogas production have the potential to create economic value and at the same time minimize negative impacts from slurry. However, their widespread application depends on factors such as local conditions, technological infrastructure, and policy support. Future studies should focus on optimizing manure management technologies, cost effectiveness and better assessing their environmental impacts. These efforts will play an important role in reducing pollution from animal manure and increasing the sustainability of the agricultural sector.

Declarations

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Osman Sönmez; Design: Osman Sönmez.; Data Collection or Processing: Fatma Nur Kılıç.; Literature Search: Fatma Nur Kılıç.; Writing, Review and Editing: Fatma Nur Kılıç, Osman Sönmez

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