Review

Research Progress and Analysis on Comprehensive Utilization of Livestock and Poultry Biogas Slurry as Agricultural Resources

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Abstract: Anaerobic fermentation of organic waste, such as livestock manure, in biogas projects is an environmentally friendly and effective treatment method. The resulting biogas, mainly composed of methane, is a combustible gas with energy properties, while the digestate, containing nutrients such as nitrogen (N), phosphorus (P), potassium (K), and other organic matter, can be used for agricultural irrigation. This article analyzes the current situation of resource utilization of livestock manure in various countries and the progress of biogas projects. It introduces the process, composition, and commonly used filtration methods before applying the digestate to farmland. The summary focuses on the improvement of crop quality, enhancement of soil fertility and the risks of pollution, and environmental hazards associated with the utilization of biogas slurry. The limitations and corresponding solutions for the agricultural utilization of livestock digestate are discussed, and recommendations are made for the technology of digestate irrigation and application to farmland.

Keywords: agricultural application; anaerobic fermentation; biogas slurry; irrigation; poultry and livestock manure

1. Introduction

Agriculture is the foundation of the economy and the basis of people’s livelihood; it can be said that it is the foundation for the development of human society. China, as a land power with an area of 9.6 million square kilometers and a population of nearly 1.4 billion, has an agricultural population of nearly 200 million—an abundant labor force. Its grain output continuously rises, ranking first in the world; however, many agricultural development problems have also made China the largest grain importer in the world [1]. On the other hand, the United States is the largest developed agricultural country in the world, as well as the largest agricultural exporter with approx. 2.2 million farms. Agriculture is a highly developed and mechanized field. For example, British agriculture meets the European standards for intensive agriculture; it has the largest average farm size and the highest share of large farms in Europe. Japan’s industry has developed rapidly since World War II, with rapid progress in agricultural modernization. From 1955 to 1975, Japan’s agricultural machinery and tools increased from 90,000 to 500,000 units [2]. The Netherlands has a land area of only over 40,000 square kilometers but remains famous for its high-quality agricultural products. It has a greenhouse building area of 110 million square meters, accounting for a quarter of the global glass greenhouse area. The Netherlands’ facility agriculture is highly automated and informatized [3].

Further, water has an important role in agricultural production; irrigation consumes ~70% of freshwater from global surface water and groundwater systems [4]. During its founding, China faced multiple problems, including low efficiency in utilizing river water resources and extremely poor farmland irrigation infrastructure. Due to the attention of
the national government and decades’ worth of efforts, the nationwide irrigated farmland area increased significantly, reaching 67.8 million hectares by 2017, four times more than at its founding stage [5]. Chinese agricultural production heavily relies on irrigation, which accounts for approximately half of the total cultivated land area and is responsible for two-thirds of value-added output [6]. According to the statistics, since the 1860s, the total amount of groundwater depletion in the United States reached 80 km², with groundwater accounting for 60% of used irrigation water [7]. Furthermore, many countries in South and West Africa currently primarily rely on rainwater for irrigation and still practice family farming. Such an approach is greatly affected by the climate; however, they are not able to benefit from climate-smart agriculture technology [8,9]. With rapid development, modern agriculture problems, such as insufficient water resources and serious pollution, have become increasingly severe, requiring irrigation systems to use excessive chemical fertilizers. Moreover, randomly discharged livestock manure is an important cause of pollution, meaning that the emergence of biogas slurry irrigation technology can save water resources. This significantly reduces pollution, thereby achieving environmental protection and sustainability in agricultural development [10].

The direct application of poultry and livestock manure as fertilizers results in a strong, stimulating odor and poses a high risk of water pollution if spread to water bodies. In addition to the odor problem, composting also poses a risk of emitting harmful gases, such as hydrogen sulfide. Therefore, biogas engineering is an excellent solution for treating organic wastewater and poultry and livestock manure. The common treatment methods for livestock manure are composting and biogas engineering. They can be classified according to Table 1. Aerobic fermentation has the advantages of a fast fermentation rate and rapid microbial proliferation. Anaerobic fermentation requires less space and allows for deep fermentation, thus preserving nutrients better. Aerobic fermentation has been widely applied due to its low technical requirements and cost, whereas anaerobic fermentation is more costly and requires higher technical expertise. The advantages of anaerobic fermentation are that it produces biogas, predominantly composed of methane, which is a combustible gas with energy properties, and the resulting digestate can be used as a specialized liquid organic fertilizer. A survey conducted in Zia village, Bangladesh, showed that the use of biogas digesters effectively saved traditional fuel and fertilizer usage, with over 50% of households reducing their expenditure through biogas digestion [11]. The biogas project has ecological and social benefits, as well as certain economic benefits. Taking the survey results of 294 biogas plants in Bangladesh as an example, the profit of small-scale biogas plants is USD 143.07 per year, and that of large-scale biogas plants can reach USD 142.17 per year [12]. Germany, China, and India have become leaders in biogas plant construction, with biogas technology being widely adopted in Germany due to higher electricity prices and policy support [13]. In some developing and underdeveloped countries, the contribution of biogas to the global renewable energy structure is still far below its potential level. The initial construction cost is a major factor constraining development. Take Pakistan as an example: the country is expected to have an average electricity supply–demand gap of about 7000 MW in 2022. Over the past decade, a series of energy policies, such as “The Alternative and Renewable Energy Policy 2019”, have been formulated, and subsidies ranging from USD 65 to USD 400 have been provided based on the size of biogas digesters. However, the imbalanced financial situation of the power system has led to a cycle of debt [14]. Technological barriers are also a major obstacle to development, especially for developing countries. Small-scale or household biogas digesters are commonly used in developing countries, operated by ordinary people such as farmers, and lack technical operators and industrial-scale digesters. Utilizing poultry and livestock manure for anaerobic fermentation is an excellent solution for the large-scale treatment of agricultural waste, reducing emissions, and lowering pollution risks. Biogas slurry, as a biogas engineering product, is an important part of the circular agricultural economy and has received attention from many countries [15–17].
Table 1. Comparison of livestock manure fermentation methods.

<table>
<thead>
<tr>
<th>Fermentation Method</th>
<th>Windrow Composting</th>
<th>Static Composting</th>
<th>Grooved Composting</th>
<th>Reactor Composting</th>
<th>USAB</th>
<th>USR</th>
<th>CSTR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scope of application</strong></td>
<td>Small and medium farms</td>
<td>Small and medium farms</td>
<td>Medium and large farms</td>
<td>Highly automated small and medium farms</td>
<td>Large- and medium-sized biogas digesters in warmer climates</td>
<td>Large- and medium-sized biogas digesters in warmer climates</td>
<td>Wide range of applications</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Manual or mechanical regular turning, simple operation, and low cost</td>
<td>Mechanical ventilation, simple operation, low cost, and short fermentation period</td>
<td>Insulation and energy-saving, easy odor control, and short fermentation cycle</td>
<td>Capable of handling high COD loads with a removal rate of over 90%</td>
<td>Suitable for processing high-solids and suspended solid materials, high gas production efficiency</td>
<td>Wide adaptability to feedstock, uniform temperature distribution inside the digester, and high gas</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Additional additives, prone to climate impact, and long fermentation period</td>
<td>Additional additives, prone to climate impact, and long fermentation period</td>
<td>Small individual processing capacity, higher cost</td>
<td>Poor impact resistance, suspended solid content needs to be controlled below 100 mg/L</td>
<td>The anaerobic digestion generates high levels of COD in the effluent</td>
<td>High construction costs, large volume digestion tanks, and long processing time</td>
<td></td>
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</tbody>
</table>

Some of the developed European countries and America started to search for ways to deal with organic waste as early as the 1970s. Industry promoted the development of biogas engineering, benefitting agriculture [18]. European countries have introduced relevant laws and policies, along with providing significant subsidies. Denmark has paid attention to the treatment of organic waste, such as manure, since 1970, and started to build biogas plants centrally in 1985. It has 20 centralized factories and more than 30 farm-scale factories. Between 2008 and 2020, it issued several measures to accelerate the development of biogas technology and facilitate its deployment [19,20]. The Netherlands, an animal product exporter and an agricultural country with nearly half of its land area used for agriculture, began research biogas engineering technology in 1978 in an attempt to find a way to deal with excessive poultry manure. Since 1984, a series of regulations on poultry manure emissions have been introduced [21]. The United States and Germany, among others, also have manure management laws. In some developing countries, anaerobic fermentation technology started late and was developed slowly. Most (e.g., Indonesia and Ghana) mainly use low-tech and low-cost poultry manure treatment methods, such as composting [22]. In some countries in Africa, such as South Africa, Namibia, Botswana, etc., due to economic, policy, training mechanism and other issues, biogas projects are still in their infancy [23]. Bangladesh had a total of about 42.49 million tons of agricultural waste between 2012 and 2013. The National Biogas and Manure Program produced 200,000 tons of organic fertilizer and reduced the use of 28,000 tonnes of fertilizer [24]. Pakistan’s livestock growth is growing at an annual rate of 4%, with a total of about 300 million tons of manure produced in 2021. However, the Ministry of Finance reported that biogas generation accounted for only 0.98% of the total electricity generation. This indicates significant room for improvement in the country’s livestock manure utilization and biogas projects [25].
China and India have established good biogas engineering systems. As of 2020, the total livestock population in India was approximately 512 million. Among them, the world’s largest cattle herd resides in India, with milk production accounting for 22% of the global total. The annual production of cow dung alone amounts to 730 million tons. In the years 1981–1982, the Ministry of Non-Conventional Energy Sources initiated the National Biogas Development Program, promoting small-scale biogas plants [26]. India mainly uses fixed dome biogas plants [27]. By 2013, biomass power accounted for 18.63% of India’s total renewable energy generation [28]. Approximately 34.3% of Indian households are using household biogas digesters [29]. India has huge potential for domestic bioenergy production due to its high and stable temperatures, providing favorable conditions for biogas fermentation. It is estimated that by 2040, India will have a total livestock population of 1.555 billion, with a biogas potential of 310 to 655 billion cubic meters per year [30]. China annually produces approximately 1.4 billion tons of agricultural waste that is available for biogas production. In recent years, significant efforts in promoting green and economic agricultural recycling systems were made. China began to promote the “pig–biogas–fruit” ecological agriculture model in the 1980s, especially in rural areas of southern China. Such an approach was widely promoted on a large scale in some of the small watershed areas by subsidizing the construction of biogas digesters. This was carried out to balance ecological environmental protection and economic development while developing a circular economy [31,32]. Chinese biogas projects are characterized by poultry and livestock manure being the key raw materials. According to the “13th Five-Year Plan for National Rural Biogas Development”, between 2003 and 2015, there were 11,057 biogas projects with poultry and livestock manure as the primary raw material; the main form was small household biogas digesters. By the end of 2009, China ranked first in the world in the number of rural household biogas digesters [33]. In agriculture, the versatility of biogas slurry was noted and can partially replace chemical fertilizers, pesticides, or soak seeds in biogas slurry; it can also be used as a nutrient solution for soilless cultivation. Furthermore, biogas slurry irrigation is a technology that can consume large amounts of biogas slurry reasonably while being safe and efficient in circular agriculture concepts. Hence, it has development prospects. However, currently, problems such as high processing costs and lack of farmland absorption limit the full utilization of the nutrients. A common problem in multiple countries is low water resource utilization efficiency and poor stability of the biogas slurry quality, which lead to a loss of nutrients, finally resulting in soil structure damage and groundwater pollution. Although the output value of animal husbandry is constantly increasing, management of agricultural waste remains imperfect, with a lack of professional technical training. The lack of such training often leads to inadequate treatment before application to fields, resulting in low comprehensive utilization levels.

In this paper, the authors first introduce the production process and composition of biogas slurry. Next, the filtration methods for suspended solids and heavy metals in biogas slurry are explained. Finally, the impact on crops, soil, and the environment from agricultural use are discussed and current irrigation problems are analyzed; solutions are also proposed.

2. Production, Composition Analysis, and Filtration of Biogas Slurry

Biogas slurry is a residual liquid obtained through the anaerobic fermentation treatment of organic matter, such as poultry and livestock manure, rural domestic sewage, urban garbage, and crop straw. In nature, it is generally weakly alkaline to neutral and bright brown in color [34,35]. After a harmless stabilization treatment, biogas slurry can be used as a raw agricultural fertilizer material; its production process is shown in Figure 1. The main processes occurring inside the anaerobic fermentation tank involve hydrolysis, acidogenesis, and acetogenesis, which facilitate the fermentation of animal manure and the production of biogas slurry. The organic waste is broken down and evenly mixed before being added to an anaerobic environment containing various bacteria, fungi, and yeasts. Through a series of reactions, such as hydrolysis, acid production, acetification, and
methane production, biogas containing large amounts of combustible gases (i.e., methane, carbon dioxide), residual biogas slurry, and biogas residue are obtained [36,37]. This process simultaneously produces renewable energy and bio-fertilizer liquid. The liquid part accounts for 90–95% of the total product mass, and the process as a whole is characterized by sustainable development in terms of agricultural recycling [38]. During biogas slurry production, organic waste is degraded through anaerobic fermentation, but nutrients such as nitrogen phosphorus potassium are preserved in the residue. In comparison with a biogas slurry of equal mass, biogas residue contains nearly twice as many nutrients, including organic matter vitamins. At the same time, the heavy metal content in biogas residue is also higher. According to a sampling analysis by Huang [39], a large amount of worm eggs was detected in biogas residue, while slurry had better hygiene conditions. Therefore, comprehensively using biogas slurry for agriculture is undoubtedly a better choice.

**Figure 1.** The process of generating biogas slurry.

Due to the high nitrogen content during the anaerobic fermentation, biogas slurry is usually weakly alkaline to neutral; however, its pH value is also affected by factors such as the type of organic waste, collection area, and treatment level, and fluctuates within a certain range. Taking poultry and livestock manure as an example, Dong [40] analyzed the literature and concluded that, due to the high nitrogen content in chicken manure, biogas slurry made from it has a significantly higher average pH value than that obtained from cow or pig manure.

In addition to a suitable pH value, the large amount of biogas slurry nutrients is another important reason it can be used as an agricultural fertilizer. Neve [41] concluded that biogas slurry fertilizer contains a large share of organic carbon. Further, its treatment technology is mature and stable, and as such, can provide organic matter to soil, increasing soil organic carbon [42,43]. It can be used as a soil amendment when applied appropriately. Nitrogen is an important nutrient required for crop growth. In traditional practices, directly using manure as fertilizer largely meets the crop demand for nitrogen [44]. In biogas slurry production, only a small amount of nitrogen in poultry and livestock manure is absorbed by microorganisms in the anaerobic fermentation tank. While retaining nutrients, the nitrogen recovery in properly treated biogas slurry is between 10% and 20% larger than that in untreated poultry and livestock manure. As such, it is a relatively stable source of nitrogen [45]. The phosphorus content in biogas slurry is usually much smaller than that of nitrogen, assuming a balanced ratio between solid and liquid phases. Experiments have shown that anaerobic fermentation of poultry and livestock manure does not affect the availability of fertilizer phosphorus. On the other hand, the ratio of nitrogen to phosphorus in biogas slurry is usually relatively stable. Most potassium elements in plants are dissolved in the cell sap. Following anaerobic fermentation, they remain dissolved in liquid potassium elements in biogas slurry and have high bioavailability, mainly being found in water-soluble form; they provide a good source of potassium fertilizer [46,47]. In addition to major nutrients, such as nitrogen, phosphorus, and potassium, biogas slurry also contains trace elements of calcium, iron, and magnesium, as well as nutrients such as amino acids and proteins, with specific contents depending on the raw material [48].

In addition to substances beneficial to crop growth, biogas slurry also contains a certain amount of heavy metal elements and antibiotics. Their content is affected by many factors, among which the raw material type has the greatest impact. Aiming to accelerate
the growth of poultry and livestock and prevent epidemics, farms use feed with added zinc oxide and copper sulfate. The trace elements, such as calcium and magnesium, found within participate in multiple chemical reactions during processing, changing their chemical forms. As a result, poultry and livestock manure contains a large number of heavy metal elements. After processing, these heavy metal elements and antibiotics enter the biogas slurry; hence, excessive use of biogas slurry can lead to heavy metal accumulation in the soil, posing a risk of soil pollution [49,50]. Samples of pig manure and cow manure before and after anaerobic fermentation are shown in Table 2. The manure used in this study was obtained from the Guizhou University farm, with a total quantity of 1000 kg. The anaerobic fermentation system employed a CSTR reactor. Before and after fermentation, the components were measured. The nitrogen content was determined using the Kjeldahl method with a digestion unit. The phosphorus content was determined using the ammonium molybdate spectrophotometric method. The potassium content was measured using a flame photometer. The total amount of copper was determined using the BCR extraction method. Therefore, filtering is an essential step before applying biogas slurry to crops. This is due to the large number of suspended particles and colloids in the biogas slurry. Further, using biogas slurry for irrigation will likely cause pipe blockages and reduce irrigation efficiency. Additionally, the large number of heavy metal elements contained in biogas slurry can affect crop growth; hence, they must be filtered out as much as possible.

Table 2. Comparison of composition of livestock manure before and after anaerobic fermentation.

<table>
<thead>
<tr>
<th>Fermented Raw Materials</th>
<th>Pig Manure</th>
<th>Cow Manure</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Before Fermentation</td>
<td>After Fermentation</td>
</tr>
<tr>
<td><strong>NH₄⁺ (mg/L)</strong></td>
<td>517</td>
<td>580</td>
</tr>
<tr>
<td><strong>NO₃⁻ (mg/L)</strong></td>
<td>310</td>
<td>62</td>
</tr>
<tr>
<td><strong>Soluble phosphorus (%)</strong></td>
<td>22.4</td>
<td>1.35 ± 0.03</td>
</tr>
<tr>
<td><strong>Total Cu (mg/L)</strong></td>
<td>3.5 ± 0.1</td>
<td>0.7 ± 0.04</td>
</tr>
</tbody>
</table>

Through research, many options for filtering harmful substances, such as suspended matter and heavy metal elements, in biogas slurry were made possible. Liu [51] used stainless-steel filters with appropriate pore sizes for multiple screenings, achieving a removal rate of 79.56% for large suspended particles in the biogas slurry, while Liang [52] compared the performances of natural sedimentation, centrifugal filtration, coagulation, and using filter bag devices for filtering the biogas slurry. It was concluded that natural sedimentation and centrifugal filtration yielded the best outcomes in removing suspended matter with a particle size > 10 µm, considering the comprehensive performance and cost factors. Bio-based filter materials were also proven to be usable. Zhang [53] proposed that filter cakes made from corn stalks can be used for filtering while also increasing the potassium content in the filtrate. Next, Song [54] observed that sawdust and slag dust can also form filter cakes. In addition, another study has shown that algae can adsorb heavy metal elements from the filtrate [55]. Shan et al. [56] proposed that ultrafine magnetic biochar and activated carbon can filter out the suspended particles and adsorb tetracycline antibiotics. Zeolite, as a natural porous medium, effectively adsorbs organic pollutants [57,58]. It should be noted that the performances among the chemical coagulation methods differ. Wang [59] stated that chemical coagulation both filters and changes the diameter and surface electrical properties of the suspended matter. However, Lee [60] pointed out that inorganic coagulants increase the metal concentration of liquids and produce toxic metal hydroxides. Moreover, cationic coagulants widely used in polymer organic coagulants can achieve charge neutralization with heavy metal ions in sludge liquor. Their performance is better than that of inorganic coagulants; however, they have a low charge density and low extraction method reliability [61,62]. After analyzing the advantages and disadvantages of several chemical flocculants, Lee et al. [63] proposed using a mixture of materials. It was
suggested to combine the effective components in a hybrid substrate, the performance of which changes with the component types and ratios. In addition to physical filtration and chemical coagulant filtration, electrocoagulation has become a common method for sludge liquor filtration. This is due to its simple operation efficiency and easy automatic control characteristics.

In addition to the filtering function, electrocoagulation can also neutralize the pH of a slurry [64]. The principle of “electrocoagulation filtration for removing impurities from biogas slurry” is shown in Figure 2. This method achieves the removal of suspended impurities in biogas slurry by precipitating metal ions and hydroxide ions, which then aggregate with suspended solids. The specific process is as follows. After applying a direct current, metal ions on the anode surface are electrolyzed, and hydroxyl radicals are released on the cathode surface, releasing hydrogen gas. Electrons move freely from the cathode to the anode, destroying the stability of the surface charges on the suspended particles. The metal ions, suspended particles, and hydroxyl radicals react, forming flocculent aggregates. Some flocculants are carried to the top of the liquid column by hydrogen bubbles, while some sink to the container bottom. Among them, aluminum and iron are commonly used materials for anodes. Some studies have also pointed out that zinc and copper can be used to reduce costs [65,66]. The electro-flocculation method can filter out various pollutants in biogas slurry, including suspended particles, heavy metal elements, sulfides, and fluorides [67].

![Figure 2. The process of formation of electro-flocculation.](image)

Physical filtration and adsorption methods are inexpensive and have a low operating threshold, but their processing capacity is limited, failing to meet the needs of large-scale projects. Chemical coagulation has a good filtration effect and large processing capacity; however, it also produces a large amount of sludge while also resulting in poor stability of the product composition. Electrocoagulation has a large processing capacity, better effects, reduced pollution, and safe product composition, while on the other hand, the long-term use of electrode plates leads to reduced coagulation efficiency, requiring frequent replacement of the electrode plates; hence, its long-term use cost is relatively high. To sum up, the choice of biogas slurry filtration method mainly depends on the scale and cost. For large-scale biogas slurry filtration, both chemical coagulation and electrocoagulation can be used. The combination of organic and inorganic coagulants in chemical coagulation has the best effect and is suitable for filtering biogas slurry with a relatively stable composition when the cost is limited. Lastly, electrocoagulation is suitable for biogas slurry filtration projects with strict requirements on the composition of the filter products, which also have sufficient funds.
3. Agricultural Application of Biogas Slurry

3.1. The Impact on Crops

The value of biogas slurry in agriculture has gradually been discovered as the related biogas projects have advanced. In 2014, China clarified the definition and technical indicators for anaerobic digested fertilizer and biogas slurry fertilizer, while the quality requirements for agricultural use were released in 2021, aiming to regulate agricultural use (see Table 3). Class I comprises herbaceous crops, Class II comprises edible crops, and Class III comprises non-edible crops. There is no requirement for the nutrient content. Biogas slurry with inappropriate pH, excessive insect eggs, or excessive heavy metal elements can be toxic to crops and cause pollution to soil and water bodies; therefore, strict restrictions are needed on the harmful substances in the biogas slurry before it is used for land application.

Table 3. Quality requirements for agricultural sludge liquor in China.

<table>
<thead>
<tr>
<th>Non-Concentrated Biogas Slurry Fertilizer</th>
<th>PH</th>
<th>Water-Insoluble Matter (mg, L)</th>
<th>The Death Rate of Ascaris Eggs, %</th>
<th>Total Arsenic (mg, L)</th>
<th>Total Chromium (Calculated as Hexavalent, mg, L)</th>
<th>Total Cadmium (mg, L)</th>
<th>Total Lead (mg, L)</th>
<th>Total Mercury (mg, L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>5.5~8.5</td>
<td>≤50</td>
<td>≥95</td>
<td>&lt;0.3</td>
<td>≤1.3</td>
<td>≤0.04</td>
<td>≤1.2</td>
<td>≤0.4</td>
</tr>
<tr>
<td>Class II</td>
<td>5.5~8.5</td>
<td>≤50</td>
<td>≥95</td>
<td>&lt;0.4</td>
<td>≤1.9</td>
<td>≤0.06</td>
<td>≤1.6</td>
<td>≤0.5</td>
</tr>
<tr>
<td>Class III</td>
<td>5.5~8.5</td>
<td>≤50</td>
<td>≥95</td>
<td>≤10.0</td>
<td>≤50</td>
<td>≤3.0</td>
<td>≤50</td>
<td>≤5.0</td>
</tr>
</tbody>
</table>

Biogas slurry can be used in facility crops; many studies on the optimal concentration of biogas slurry for improving crop yield and quality have been carried out. Lü [68] found that lettuce achieves the maximum yield when the ratio of biogas slurry to water is 1:4. Yang et al. [69] discovered that the biogas slurry concentration should be controlled within a certain range; further, its relationship with the lettuce yield was not linear. Moreover, biogas slurry fertilizer can significantly increase the dry matter in lettuce leaves. Xu [70] found that various concentrations of biogas slurry can increase the yield up to 56.7% and the moisture content by 3.6%. The nitrate content in the leaves was significantly lower than that obtained using traditional chemical fertilizers. Lü et al. [68] also found that spinach will also achieve the maximum yield for the biogas slurry to water ratio of 1:4. Bridget [71] conducted an experiment using cow manure biogas slurry, while an inorganic fertilizer was used as a control group; it was found that spinach plants treated with the biogas liquid fertilizer had longer roots and higher zinc content. Zheng et al. [72] found that a 20% concentration of biogas slurry had the greatest impact on tomato quality. Additionally, it was found that tomato development required different nutrients during different growth stages. During the seedling stage, it was advantageous to reduce the concentration of biogas slurry and reduce the application of nitrogen fertilizer. Jothi [73] pointed out that biogas slurry can both accelerate tomato flowering and fruiting and reduce the probability of root-knot nematode disease in tomatoes. The best effect was discovered for the biogas slurry concentration of 10%. Biogas slurry contains ammonium salts and B vitamins, as well as some antibiotics, which prevent epidemics and pests. Zhang et al. [74] experimented on citrus trees, finding that using biogas slurry fertilizer increased the pest control efficacy against aphids by 26.2% compared to using pesticides. Next, Cao et al. [75] experimentally demonstrated that the use of a biogas slurry fertilizer has sustainable practical inhibitory effects on watermelon wilt disease. Similarly, Li et al. [76] demonstrated such inhibitory effects on cucumber wilt disease. Yu et al. [77] screened 11 plant pathogens and found that biogas slurry had good inhibitory effects on Penicillium sp., Botrytis cinerea, Alternaria solani, and F. oxysporum f. sp. Among them, Alternaria solani seriously impacts cucumber cultivation in plastic greenhouses. Fusarium oxysporum can cause wilt disease in more than 100 plants, including melons, eggplants, and bananas, and seriously affects crop quality. The difference in irrigation methods also impacts crop growth. Tyler et al. [78] adopted underground
drip irrigation, finding that there are more young fruits in tomatoes irrigated with biogas slurry than mineral nitrogen fertilizer. Zheng et al. [72] further studied and compared the effects of surface irrigation and hole irrigation on tomato growth at different stages. Hole irrigation combined with biogas slurry during high water demand periods, such as fruit expansion and maturity, had the optimal growth-promoting effect. Liu et al. [79] used Chinese cabbage as a case to conduct a control experiment on spray irrigation and drip irrigation. Since only a small amount of the sprayed biogas slurry was quickly absorbed by the leaves and the majority of it fell into the substrate near the roots, the growth advantage of biogas slurry-irrigated crops was generally concentrated in the roots. The mineral content in the root environment was lower than that in crops treated with drip irrigation. Finally, it was concluded that the growth was greatly affected by the soil mineral content, while the dry matter increase was slightly lower.

The use of biogas slurry in paddy field crops has also been a subject of study. Compared to the use of chemical fertilizers throughout the process, combining chemical and biogas slurry fertilizers can both increase the yield and reduce costs. Compared with the whole process of chemical fertilizers, the combined fertilizer composed of biogas slurry and a chemical fertilizer can effectively increase the soil organic carbon, thereby enhancing the crop yield. Increasing the soil organic carbon content by 1 g/kg can lead to a rice yield increase of 302 kg/ha [80,81]. Li et al. [82] found that combining biogas slurry and chemical fertilizers resulted in an average rice yield of 5.1% higher than when using chemical fertilizer alone. Tang Wei et al. [83] discovered that when the amount of biogas slurry was appropriate, the protein content in rice was higher than that obtained when irrigated with water or chemical fertilizers, with an increased rate exceeding 20%. Wu et al. [84] found that corn yield quality was optimal when the biogas slurry to chemical fertilizer ratio reached 1:1. Next, Muhmood et al. [85] stated that biogas slurry has a stronger yield-increasing effect on summer corn than winter corn. The combined use of biogas slurry fertilizer and inorganic fertilizer reduced the amount of used inorganic fertilizer and increased the corn yield. In addition to crop yield, Huang et al. [86] pointed out that biogas irrigation also increased the yield of both corn ears and stalks. The biogas slurry composition determines its suitability for irrigation. Huang et al. [87] proposed that multiple applications of biogas slurry during the rice growth process provide better results than a one-time application. This is because nutrients found in biogas slurry are mostly fast-acting components, meaning that a one-time application cannot guarantee subsequent fertility.

Regarding the growth of crops, biogas slurry’s advantages far outweigh its shortcomings; it increases crop yield, accelerates growth, increases the crop protein content, and prevents some epidemics and pests. However, research on the safety of biogas slurry itself is lacking. For example, excessive use might lead to excessive accumulation of nitrogen in crops, causing peanut disease, as well as other nitrogen fertilizer diseases. Next, excessive heavy metal elements can cause poisoning, while untreated pathogens and harmful organisms (e.g., insect eggs) can spread pests. Further, unfermented biogas slurry can easily cause root burning, and high-concentration irrigation under high-temperature conditions can easily cause dehydration. Generally, biogas slurry is harmful to crops mainly when unreasonably applied. Therefore, with a good understanding of biogas slurry irrigation technology and the selection of an appropriate irrigation concentration, biogas slurry can take the role of both fertilizer and pesticide while also being more environmentally friendly and easier to obtain.

3.2. The Impact on Soil

Biogas slurry contains nutrients such as nitrogen, phosphorus, and organic matter, which positively impact the soil environment. At the same time, various heavy metal elements and antibiotics within it affect the soil negatively, attracting researchers’ attention.

The appropriate application of biogas slurry can improve the vitality of soil microbial communities and enhance their fertility. Tang [83] applied biogas slurry to rice–wheat fields in reclaimed coastal land and found that using biogas slurry increases the amount of effective nitrogen and phosphorus in the soil, achieving a balanced supply. Based on
the experiments, Chen et al. [88] concluded that the ammonia nitrogen and organic matter in biogas slurry help crop growth, while also remaining in the soil in large quantities along with residual quick-acting phosphorus and potassium, increasing its fertility. Some nitrogen elements within the biogas slurry exist in the form of nitrates. Zheng et al. [89] performed several control experiments, finding that the corn irrigation position does not lead to an increase in nitrate-nitrogen concentration in the root zone soil with crop growth; the nitrate-nitrogen concentrations were all within safe limits.

Compared to nitrogen elements, the carbon content in biogas slurry is relatively low. Wentzel et al. [90] assumed that long-term application of biogas slurry will not significantly increase soil organic carbon levels; the same conclusion was attained experimentally by Thomas et al. [91]. Heavy metal pollution is among the reasons why biogas slurry irrigation safety is being questioned. Bian et al. [92] used pig manure and straw to produce biogas slurry and carried out separate experiments on economic crops and field crops in the Taihu Lake Basin. It was found that Zn, Pb, and Cd in the soil obtained high EF values, and the pollution degree of the vegetables and grains planted on them exceeded Chinese quality standards. The experiment determined that the average heavy metal content in wheat root soil was higher than that in rice root soil, while the heavy metal concentration in leafy vegetable root soil was higher than that in their fruit counterparts. Therefore, it was speculated that Pb, Cd, and other heavy metals in biogas slurry-irrigated soil will be affected by the physiological characteristics of the crop. The above-presented experiments have conflicting conclusions, indicating that there is a risk of heavy metal concentrations exceeding standards when irrigating using biogas slurry. Hence, its usage should be strictly controlled. Hg is one of the significant pollutants in soil, and as such, should be strictly monitored as a toxic and harmful element. Liu [93] studied the effect of pig manure-derived biogas slurry on the soil during peanut cultivation. The authors found that the Hg content increased 26.67 times, which still remained within the acceptable range, but with a high safety risk. Mariusz et al. [94] pointed out that antibiotics might affect microbial function, structure, and genetic genes in the soil since some can degrade antibiotics, while the more sensitive ones might be killed. This will, in turn, affect microbial diversity.

The impact of biogas slurry on soil is affected by soil conditions, climate, and crop types, among other factors. Its advantages are the rich nutrients that can improve the soil structure, promote soil microbial activity, and effectively increase soil fertility. However, multiple experiments have shown that biogas slurry irrigation does indeed lead to an increase in soil heavy metal content, possibly exacerbating soil salinization. Due to the low peak temperature of anaerobic fermentation and higher antibiotic content in poultry manure compared to traditional composting, it might kill some of the soil microbes, causing an imbalance in the soil environment. Within studies analyzing the impact of biogas slurry on soil, there is a lack of comprehensive analysis of biogas slurry composition, crop types, and soil environment. After fully investigating the soil conditions themselves, accurately quantifying N, P, and K, in addition to other major soil elements should be undertaken to formulate specific irrigation strategies. Additionally, anaerobic fermentation technologies, such as adding pasteurization steps to digesters, should be improved to remove pathogens. Lastly, multi-stage filters with targeted filtering methods could be constructed to control harmful substances within an acceptable range.

### 3.3. The Impact on the Environment

The impact of biogas slurry on the environment is mainly reflected in two aspects: the impact on water bodies and the impact on air. Based on the analysis of carbon, nitrogen, and water footprints, organic rice cultivation can reduce greenhouse gas emissions compared to traditional crop cultivation. It also enhances the organic carbon sequestration capacity. Biogas slurry, as a liquid organic fertilizer, can effectively reduce the use of chemical fertilizers and alleviate the environmental pollution caused by agricultural fertilizer application [95]. Most of the nitrogen in biogas slurry exists in the form of ammonia nitrogen. After being nitrified by soil, it is transformed into negatively charged nitrate-nitrogen. Since soil carries
negative electricity, nitrate-nitrogen easily flows into the lower layer with soil seepage, entering the groundwater. As such, it poses a risk of eutrophication of water bodies, a phenomenon known as ammonia nitrogen leaching. There are many reasons for ammonia nitrogen leaching; Huang et al. [96] pointed out that such a risk is positively correlated with the level of nitrogen elements in biogas slurry. Further, Zeng [97] stated that excessive biogas slurry irrigation and excessive rainwater accelerate this pollution process. Möller et al. [98] experimentally determined that the previously planted crop also affects the soil nitrate leaching. Zhang et al. [99] concluded that river water has stronger nitrification, and that an excessive nitrate content might further affect marine ecosystems, causing massive proliferation of toxic algae and hypoxia. Finally, heavy metals in biogas slurry, as well as possible parasites and viruses, also pose a risk to water bodies.

Existing studies have shown that compared to chemical fertilizers and the direct use of poultry manure, biogas slurry irrigation increases the volatilization of gases such as NH$_3$, CH$_4$, and N$_2$O. Möller [98] speculated that this phenomenon is due to the smaller viscosity of biogas slurry, which is caused by anaerobic digestion and its higher pH. Temperature is another influencing factor. The ammonia volatilization rate caused by biogas slurry irrigation in summer is greater than that during the winter; hence, it is speculated that soil microbes are more active at a higher temperature. Ammonia gas is the main alkaline pollutant in the atmosphere and an important precursor to PM2.5, and it easily reacts with other atmospheric substances, forming particulate matter. Finally, CH$_4$ and N$_2$O are gases with extremely high greenhouse effect potential; the potential of N$_2$O is 298 times greater than that of CO$_2$ [100].

Whether using methods such as composting and drying or making biogas slurry, it is difficult to avoid the environmental pollution caused by livestock manure. The above-reviewed studies point out that biogas slurry irrigation increases the water eutrophication risk. Excessive nutrients might enter the groundwater and pollute it, leading to problems such as algal blooms and the death of aquatic organisms. It can also increase the emission of greenhouse gases, such as N$_2$O and NH$_3$, causing air pollution. For this reason, measures must be taken; compared to difficult-to-handle livestock manure and the extensive use of pesticides and fertilizers, biogas slurry is a more environmentally friendly choice. When aiming to reduce the risk of pollution, it is necessary to strengthen the monitoring of biogas slurry composition and the soil environment. Doing so will reduce the possibility of pollution caused by incomplete fermentation or unreasonable biogas slurry component ratios. Moreover, developing compliant biogas storage facilities is necessary to prevent leakage and volatilization of biogas slurry. Further, public awareness of environmental protection should be increased and relevant regulations to regulate the use of biogas slurry should be introduced. Next, it is necessary to prevent excessive emissions and indiscriminate discharge and adopt scientific irrigation strategies to minimize the impact of biogas on the environment, reduce pollution problems, and improve resource utilization efficiency.

4. Discussion

4.1. Irrigation Technology

Biogas slurry can increase crop yield and improve its quality. It can also effectively improve the microbial soil environment and enhance soil fertility; however, it also has certain disadvantages. For specific crops, when the ratio concentration is not optimal, the nutrients in biogas slurry are wasted and the effect of improving crop growth will be limited. Current research indicates that the optimal improvement effect on crops and soil is achieved when the ratio of biogas slurry to chemical fertilizer is 80% biogas slurry with 20% chemical fertilizer or 75% biogas slurry with 25% chemical fertilizer. This ratio does not increase the burden on soil and the environment. Adopting the ratio of biogas slurry with chemical fertilizer for fertilization can effectively reduce the amount of chemical fertilizer. Additionally, the amount of biogas slurry used for irrigation should be quantified accurately. Excessive biogas slurry can lead to the accumulation of nitrogen and heavy
metals in crops, causing diseases and accelerating soil salinization, while also increasing the risk of nitrogen leaching.

To mitigate this issue, the United States proposed using agricultural and forestry residues to make biochar as a soil barrier. On the other hand, researchers in Tanzania believe that biogas irrigation can effectively reduce soil infertility and acidification problems. Therefore, the concentration and amount of biogas irrigation should be strictly controlled based on crop type, growth status, and soil environment. Currently, there is still a lack of research on irrigation methods. Due to its odor, flood irrigation is less commonly used in biogas slurry irrigation, while drip irrigation and spray irrigation are acknowledged as mainstream methods. Further, drip irrigation can ensure that crops absorb more nutrients, but it is costly and nozzles clog easily. Spray irrigation is suitable for large-scale irrigation but has lower nutrient utilization efficiency. In summary, suitable irrigation techniques, including an appropriate concentration, mixing ratios, and irrigation methods, can typically enhance crop yields by more than 5%. In exceptional cases, the increase in crop yield can reach up to 53.1%. These techniques aim to reduce carbon footprints and achieve optimal crop productivity. The specific implementation of biogas slurry irrigation should consider factors such as biogas composition, crops, soil, and cost to accurately select the appropriate irrigation technology, select the appropriate ratio of biogas slurry to chemical fertilizer, and develop targeted strategies.

4.2. Equipment

At present, the construction of intelligent agriculture in China is still insufficient. The application of biogas slurry is relatively rough, lacking a complete mechanism for detecting biogas slurry concentration and fertilization. As such, it cannot ensure that the concentration and nutrient content of biogas slurry is always maintained within the optimal range. Furthermore, there is also a lack of precise and automated biogas slurry irrigation equipment; hence, factories producing biogas slurry should control the degree of anaerobic fermentation and monitor the content of effective substances in each biogas slurry batch to maximize its effect on crop growth. Regarding biogas slurry, China stipulates that the total nutrient content should be \( \geq 80 \text{g/L} \); however, the actual nutrient content in untreated biogas slurry is much lower than that of inorganic fertilizers. The use of biogas slurry alone for irrigation cannot meet the nutritional needs of crops and may even cause seedling scorching and exacerbate soil salinization due to excessive salt content in the slurry. Therefore, the optimal design solution should be a combination of biogas slurry, supplementary fertilizer, and water, with the slurry being diluted appropriately to meet the nutritional needs of crops and soil. Previous studies overlooked that, before applying biogas slurry to corresponding crops, elements with insufficient content should be added based on specific crop growth needs. The amount of slurry irrigation also requires more precise control within the range to meet the crop nutrient requirements and avoid excessive emissions and environmental pollution risks.

The design and development of a new type of intelligent control device for biogas slurry irrigation should be carried out while also considering factors such as the irrigation area and cost. The sprinkler irrigation method in large-scale farmland should be selected during the fertilization process according to the differences in the required nutrients at different stages of crop growth. Next, the element content in soil should be monitored in real-time, using sensors reflecting the crop growth status. Further, an algorithm should be used to analyze the difference between the current growth status and the ideal situation, comprehensively considering environmental factors such as temperature, soil conditions, and rainfall. The water and fertilizer demand should be dynamically calculated for crops, adjusting the nutrient content of nitrogen, phosphorus, and potassium in biogas slurry. Further, the time point and the amount of biogas slurry irrigation should be determined accurately for the specific demand for each nutrient element for targeted irrigation.

The design of the biogas slurry irrigation system can refer to the integrated water and fertilizer system, incorporating PID control technology and flow monitoring technology into the system. By combining software and hardware, it is possible to achieve the connection
between the soil–crop–computer–irrigation equipment, ensuring real-time monitoring. The feedback on crop status can be achieved according to a constructed irrigation decision-making mechanism, resulting in the automatic, intelligent application of biogas slurry to crop cultivation. Doing so will also reduce ecological pressure while developing the economy and promoting the modernization of the agricultural industry.

Environmental Risks

Biogas slurry irrigation bears the risk of polluting the environment, primarily when improperly used. The annual energy consumption for nitrogen fertilizer production is approximately 100 million metric tons of standard coal, which also leads to emissions of water pollutants and soil and air pollution. As a byproduct of biogas projects, biogas slurry can be utilized as a specialized liquid fertilizer, effectively reducing the use of chemical fertilizers. In addition to nutrients beneficial to crop growth, biogas slurry also contains a variety of pollutants. There is a phenomenon that biogas slurry obtained from biogas projects has a higher heavy metal content than that obtained via household biogas digesters. To avoid harmful substances being transferred to crops and endangering human health, biogas slurry should be pre-treated before use, using filtration to remove as many pollutants as possible. At the moment, some household biogas digesters in China still have insufficient filtration and the standards related to agricultural biogas slurry are not followed. Supervision of the biogas slurry filtration process needs to be strengthened.

Excessive irrigation with biogas slurry will increase the soil nitrogen concentration and burden on water and the atmosphere. Similarly, excessive biogas slurry will increase the risk of water pollution caused by nitrate-nitrogen leaching, while some of the small organic molecules might enter groundwater through soil moisture. A large number of quick-acting elements in biogas slurry will increase soil microbial activity, accelerating soil nitrogen decomposition, and, finally, leading to emissions of pollutants such as ammonia gas, exacerbating the greenhouse effect.

In Denmark, acidified slurries are commonly used to reduce ammonia emissions from livestock manure, while other countries choose biochar and nitrification inhibitors to reduce ammonia volatilization. Current research on the performance of the agricultural use of biogas slurry is mostly concentrated in European countries and China, while environmental awareness in African countries remains limited by technical level, leading to greater pollution risks.

The Regulations on Prevention and Control of Pollution from Large-scale Livestock and Poultry Farming passed in China in 2013 stipulate that the treatment and discharge of livestock manure must comply with national and local regulations, without exceeding the total control indicators. In the “Technical Specifications for the Application and Ecological Utilization of Biogas Slurry” in Zhejiang Province, China, it is explicitly stated that the mortality rate of helminth eggs in biogas slurry must be \( \geq 95\% \). Therefore, it is necessary to improve the requirements for filtration treatment and strictly control the amount of biogas slurry formulation used. Finally, relevant policies should comprehensively consider factors such as crop soil conditions and climate, and it is necessary to develop reasonable plans and avoid excessive irrigation. During the process of biogas slurry application in farmland, selecting an appropriate irrigation ratio and developing an intelligent control system can help reduce the risk of environmental pollution while meeting the nutritional needs of crops and soil through a proper combination of biogas slurry, fertilizers, and water.

5. Conclusions

Water resource shortage, serious agricultural pollution, and large quantities of livestock manure with difficult treatment are all existing problems in current global agricultural development. Among them, China alone produces 3.05 billion tons of livestock and poultry manure annually. It can be feasibly solved by biogas slurry irrigation. Further, its use effectively improves crop quality and yield but poses risks of polluting soil and the environment. Currently, limitations in the application of biogas slurry remain in many countries. There are generally differences in the development level of animal husbandry
in different regions, as well as the uneven production of poultry and livestock manure. Further, there is a lack of sufficient supporting farmland needed to consume biogas slurry for large-scale biogas projects and the means of storing existing biogas slurry are limited. In addition, the current research on the improvement of crop quality and soil fertility by biogas slurry is still in the experimental stage, and there is a lack of real field application. In the actual biogas slurry returning to the field, it is a better choice to use combined biogas slurry and a chemical fertilizer or add nutrients to supplement the biogas slurry components. Aiming to promote the utilization of agricultural resources from biogas slurry, in the actual process of returning to the field, biogas slurry can be regarded as a special liquid fertilizer. Therefore, related technologies, such as water and fertilizer integration, can be used as a reference. It is necessary to develop safe and efficient biogas slurry irrigation equipment. Additionally, a soil–water–crop–biological four-in-one technical system for biogas slurry irrigation should be established. In other words, economical, applicable, and comprehensive supporting technologies should be proposed to improve the efficiency of agricultural resource utilization from poultry and livestock manure.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are openly available in reference number [1–7,11,12,14–24,26,30].

Conflicts of Interest: The authors declare no conflict of interest.

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