Optimizing biomass energy production from livestock waste to reduce environmental pollution with a nexus model approach

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ARTICLE INFO	ABSTRACT
	Environmental pollution driven by fossil fuel consumption has become a major global concern, motivating policymakers and scientists to explore sustainable mitigation pathways. Biogas production from livestock manure offers a promising alternative that simultaneously substitutes fossil fuels and improves waste management. This study estimates the potential of biogas generation from livestock residues and its role in reducing environmental pressures in Orzuieh County. Polynomial linear programming was employed to optimize three objective functions using a nexus modeling framework under interval uncertainty. Results indicate that livestock manure could produce approximately 3.07×10^8 MJ of renewable energy, equivalent to 8.3×10^7 m³ of natural gas. Additionally, livestock activities were estimated to release about 1.7×10^7 kg of CO_2 emissions alongside considerable land pollution. These findings suggest that incorporating biogas technologies into regional development strategies can serve as an effective approach to decrease fossil fuel dependence, mitigate greenhouse gas emissions, and foster cleaner energy transitions while enhancing environmental sustainability.

Highlights	• Nexus model optimizes livestock waste-to-energy • Manure yields 3.07×10^8 MJ energy, cuts pollution • Cows are major methane emitters; goats top biomass source • Biogas potential equals 8.3×10^7 m³ of natural gas

1. Introduction

The reduction of fossil fuel resources, together with the release of pollutants such as carbon dioxide and their environmental effects, has led policymakers and energy planners to look for clean alternatives to reduce pollution. Biogas, as a green and renewable energy source, is considered a valuable option. When organic matter decomposes, a mixture of carbon dioxide and methane, called biogas, is produced, which can replace fossil fuels in different applications (Khoshgoftar Manesh et al., 2020). Biogas is a renewable energy source that can be used for the production of heat, electricity, and vehicle fuels (biofuels) (Timonen et al., 2019). Anaerobic digestion is a suitable alternative to conventional methods of managing organic waste and serves as an effective tool for mitigating climate change, as it ensures proper waste disposal and reduces greenhouse gas emissions (Aziz et al., 2019). Methane constitutes the largest share of biogas components. Although methane is a potent greenhouse gas, it is also responsible for the high calorific value of the mixture, making biogas a promising alternative to natural gas (Ferella et al., 2019). Animal manure, as a bioenergy substrate, allows farmers to produce biogas while mitigating diffuse agricultural pollution, including air, water,

and soil contamination (Cantrell et al., 2008). Biomass energy production is inherently connected to the land-based water–energy–food nexus (WEFN). Its complexity stems from the necessity of balancing economic gains with detrimental environmental consequences, particularly greenhouse gas emissions as well as water and soil pollution (Amini & Hesami, 2017; Li et al., 2020). One-dimensional optimization approaches cannot fully capture the interdependencies among the three interconnected systems of water, food, and energy. Most developed resource modeling techniques adopt a unidimensional perspective, whether economic, social, or environmental, or focus on a single resource. This limitation in existing methods can hinder their ability to address contemporary resource management issues, which often require multidimensional analysis (Albrecht et al., 2018). In contrast, multi-objective planning using a nexus modeling approach offers an effective means to address the complexity and multidimensionality of these challenges (Zhong et al., 2018). Focusing on a single component of WEFN without considering its interconnections can generate significant risks and unintended consequences for society (World Economic Forum, 2011).

Furthermore, when optimizing bioenergy production within an agricultural system, decision-makers frequently face uncertainties in parameter estimation due to insufficient information, natural resource variability, socio-economic fluctuations, and subjective judgments (Amini et al., 2009; Purkus et al., 2015). To address such uncertainties, this study employs an interval uncertainty approach, which is advantageous for dealing with uncertainties approximated solely by upper and lower bounds (Wang & Huang, 2014). The concept of nexus modeling initially emerged at the World Economic Forum in 2008 and was subsequently emphasized in the Bonn conferences in Germany, the Sixth World Water Forum in France in 2012, and the Rio+20 negotiations, highlighting the application of nexus-based models (Safaee et al., 2019).

The nexus modeling approach examines the influence of driving forces such as climate change, socio-economic developments, and pressures arising from population growth and increased consumption. Importantly, the WEFN should not be regarded merely as a slogan; rather, it represents a true interdisciplinary reality. This approach illustrates the interconnections among components of complex social and environmental systems. The interplay and interdependence of water, energy, and food become increasingly pronounced in the context of natural resource scarcity and security (Safaee et al., 2019). In essence, the WEFN provides a perspective on sustainable development, aiming to balance multiple objectives, including the needs and benefits of society and the environment (Hoff, 2011). However, few studies have incorporated the nexus approach alongside animal manure within an agricultural system, employing interval-based data in a multi-objective framework to optimize bioenergy production and mitigate environmental impacts. The following section reviews several studies in this field.

Oliveira et al. (2021) evaluated and optimized electricity generation from animal manure in two regions of Brazil using an optimization model and QGIS software for biogas plant allocation. They reported the average cost of biogas energy production using a fixed engine and a combined cycle as 0.2384 and 0.0974 USD per kWh, respectively. Additionally, the reduction in carbon dioxide emissions per capita was estimated to range from 6.05% to 14.52% across the studied regions. Soltan and Ehsanalah (2021) investigated the biogas production potential of animal manure in Pakistan. The results indicated that animal manure could produce approximately $87,351 \times 10^{11}$ cubic meters (m^3) of biogas, corresponding to 492.6 Petajoules (PJ) of thermal energy and 5,521 Megawatts (MW) of electricity, while simultaneously mitigating environmental pollution associated with manure disposal. Li et al. (2020) investigated bioenergy production using a nexus modeling approach. Their results demonstrated that bioenergy generation from agricultural and animal waste can optimize three objectives: the production of clean energy, the reduction of water and soil pollution, and the mitigation of greenhouse gas emissions. Balaman (2016) proposed a multi-objective planning model, incorporating both economic and environmental objectives, in which anaerobic digestion and gasification processes were combined. The biogas produced was ultimately converted into electricity in thermal and power generation units.

The objective of this study is to optimize sustainable bioenergy production for clean energy generation and environmental pollution mitigation, employing a WEFN modeling approach under interval-based uncertainty. Unlike one-dimensional optimization studies, this research examines the Orzuieyeh region from three perspectives: maximizing bioenergy production, minimizing costs, and minimizing environmental impacts. The aim is to provide a comprehensive analysis for decision-makers and policymakers through a nexus-based framework encompassing WEFN systems.

2. Materials and Methods

This study was conducted in the southwestern part of Kerman Province, one of the key regions for livestock rearing, particularly small ruminants. In Orzuieyeh County, cattle, sheep, and goats constitute the main livestock of local farmers. Orzuieyeh County is located approximately 260 km southwest of Kerman and features a tropical semi-arid climate. Climatically, it is considered one of the most suitable regions for agriculture and livestock farming within Kerman Province and its neighboring areas (Saljooghi et al., 2021).

In this section, an optimization model is developed to support sustainable bioenergy production by integrating a WEFN approach for clean energy generation and environmental pollution mitigation. Accordingly, the optimization model involves three objective functions: maximizing bioenergy production, minimizing costs, and minimizing environmental pollution. These objectives are subject to constraints related to water supply, food demand (red meat provision), livestock policies, and economic regulations. The research model is presented in three main components as detailed by Li et al. (2020).

2.1 Maximizing bioenergy production

Maximizing bioenergy production serves as an assessment of bioenergy potential. This study assumes that bioenergy is generated from animal manure. Agricultural residues have multiple applications; for instance, animal manure is commonly used for both fertilization and energy production. Animal manure provides economic benefits while also producing diverse environmental impacts. This objective function employs weighting coefficients based on real-world conditions to determine the proportion of livestock waste that can be allocated for bioenergy production. The bioenergy output is expressed in terms of equivalent standard coal (Li et al., 2020). The mathematical formulation of the first objective function is presented in Eqs. 1 to 3 (Li et al., 2020).

$$BP^{\pm}_{livestock} = BP^{\pm}_{manur} + BP^{\pm}_{urine} \tag{1}$$

where, $BP_{livestock}$, BP_{manure}, and BP_{urine} represent, respectively, the energy produced from livestock waste, energy produced from animal manure, and energy produced from animal urine.

$$BP^{\pm}_{manur} = \sum_{l=1}^{L} N_l \cdot [ME^{\pm}_l \cdot \varepsilon^{\pm}_l \cdot (\xi_{manur})^{\pm}_l (\theta_{manur})^{\pm}_l] \cdot (\delta_{livestock})_l \cdot HV \tag{2}$$

where, the variable N_l represents the number of heads of each livestock type, while the parameters ME_l and HV denote, respectively, the manure emission per animal and the calorific value of standard coal Megajoule (MJ). Additionally, the coefficients ε_l, $(\xi_{manu})_l$, $(\theta_{manu})_l$ and $(\delta_{livestock})_l$ represent, respectively, the collectable fraction of solid and liquid waste for each livestock, the dry matter content of manure, the biogas yield per unit of manure dry matter, and the ratio of biogas yield from solid and liquid manure expressed in standard coal equivalents.

$$BP^{\pm}_{urine} = \sum_{l=1}^{L} N_l \cdot [UE^{\pm}_l \cdot \varepsilon_l \cdot (\xi_{urine})_l \cdot (\theta_{urine})^{\pm}_l] \cdot (\delta_{livestock})_l \cdot HV \tag{3}$$

where, the parameter UE_l represents the urine excretion rate of each livestock (kg/head). The coefficients $(\xi_{urine})_l$ and $(\theta_{urine})_l$ denote, respectively, the proportion of dry matter in livestock urine and the emission coefficient of pollutants associated with urine for each livestock type. These parameters are critical for accurately quantifying the potential bioenergy yield and environmental impacts derived from liquid waste streams in the studied system.

2.2 Minimization of environmental impacts

The environmental side effects of bioenergy production should be considered alongside economic impacts in order to assess the sustainable development requirements of livestock farming. Broadly, there are two types of environmental pollution. The first is water and soil pollution caused by livestock waste. Common pollutants from livestock production, such as oocysts, biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium nitrogen, total nitrogen, total phosphorus, and total potassium, contaminate water and soil through surface runoff and groundwater leakage. At the same time, livestock production generates greenhouse gases, which contribute to climate change. Nitrification and denitrification of livestock manure in soils result in nitrous oxide emissions, while the application of organic fertilizers leads to methane emissions (Li et al., 2020). In summary, the mathematical formulation of the second objective function is presented in Eqs. 4 to 7 (Li et al., 2020).

$$minEL^{\pm} = (WP^{\mp}_{Livestock}) + (21E^{\pm}_{CH_4} + 310E^{\pm}_{N_2O}) \tag{4}$$

where, $minEL$ and $WP_{Livestock}$ represent the minimization of environmental impacts and the pollution released from livestock manure, respectively. The terms $21E_{CH4}$ and $310E_{N2O}$ denote the conversion of methane and nitrous oxide emissions into their carbon dioxide equivalents.

$$WP^{\pm}_{livestock} = \sum_{l=1}^{L} N_l \left[ME^{\pm}_l \cdot \sum_{pl=1}^{PL} (\phi_{manu})_{pl,l} \cdot \tau^{\pm} + UE^{\pm}_l \cdot \sum_{pl=1}^{pl} (\phi_{uri})_{pl,l} \cdot \tau^{\pm} \right] \tag{5}$$

Where, the coefficients $(\phi_{manu})_{pl,\,l}$, $(\phi_{uri})_{pl,l}$ and τ represent the pollutant emission coefficient from livestock manure, the pollutant emission coefficient from livestock urine, and the coefficient of pollutant transfer from livestock to water and soil, respectively.

$$E^{\pm}_{CH_4} = \sum_{l=1}^{L} N_l \cdot (MEF^{\pm}_l + MM^{\pm}_l) \tag{6}$$

Where, the parameters MEF_l and MM_l represent, respectively, the enteric fermentation methane emissions per animal (kg/head) and the methane emissions from manure management per animal (kg/head). In Eq. 7, NM_l denotes the emission coefficient of nitrous oxide from manure management per animal (kg/head).

$$E^{\pm}_{N_2O} = \sum_{l=1}^{L} N_l \cdot NM^{\pm}_l \tag{7}$$

The environmental impact minimization function consists of two parts. The first part represents water and soil pollution, while the second part accounts for greenhouse gas emissions. The global warming potential (GWP) is used to convert different types of greenhouse gas emissions into carbon dioxide equivalents. The GWP value is 310 for nitrous oxide and 21 for methane, indicating that the energy released by nitrous oxide and methane is 310 and 21 times greater, respectively, than that released by carbon dioxide in the atmosphere (Cardinale et al., 2007).

2.3 Minimization of costs

Cost minimization represents a core objective that captures the economic implications of bioenergy production for overall profitability. The cost components of bioenergy generation include feedstock cost (FC), energy cost (EB), labor cost (LC), and building depreciation (BD), all expressed in Iranian Rials (Li et al., 2020). The mathematical formulation of the third objective function is provided in Eqs. 8 and 9.

$$C^{\pm}_{livestock} = \sum_{l=1}^{L} (N_l \cdot CL^{\pm}_l) \tag{8}$$

Where, $C_{Livestock}$ and CL_l represent the regional livestock cost and the cost per animal, respectively.

$$CL_l = FC + EB + LC + BD \tag{9}$$

2.4 Constraints

In constrained optimization, objective functions are subject to constraints. In this study, three objective functions are subjected to five constraints.

The water supply constraint requires that the allocated water for livestock farming in the region must not be less than the consumption of the regional livestock. This constraint can be expressed as Eq. 10 (Li et al., 2020):

$$\sum_{l=1}^{L} N_l \cdot DWQL_l^{\pm} \leq WS_{livestock} \qquad (10)$$

where, the parameter DWQ_l denotes the drinking water quota per animal (m³/head), while $WS_{livestock}$ represents the total water supply available for livestock in the region (m³). The regional demand constraint for red meat consumption requires that meat production performance must at least meet the local dietary needs (i.e., self-sufficiency based on the local population) to ensure food security. This constraint is formulated in Eq. 11 (Li et al., 2020).

$$\sum_{l=1}^{L} N_l \cdot W_l^{\pm} \geq PO \cdot FD_{min}^{\pm} \qquad (11)$$

where, the parameters PO and FD_{min} represent the regional population and the minimum food demand (kg/person), respectively, while the coefficient W indicates the livestock supply required to meet the regional meat market demand.

The livestock policy constraint states that the number of each livestock type in the region should not fall below the minimum threshold to ensure the sustainable development of livestock farming. Moreover, the number of each livestock type in the optimization model must be represented as an integer, consistent with real-world conditions. This constraint is formulated in Eq. 12 (Li et al., 2020).

$$N_{min,l} \leq N_l \leq N_{max,l} \quad and \quad N_l = integer \qquad (12)$$

The economic policy constraint requires that the economic returns from livestock production should not fall below the corresponding minimum economic thresholds, in order to enhance livestock profitability. This constraint can be formulated as Eq. 13 (Li et al., 2020).

$$\sum_{l=1}^{L} N_l \cdot PL_l^{\pm} \geq EB_{livestock} \qquad (13)$$

where, PL_l and $EB_{Livestock}$ represent the price per head of livestock (Rial) and the prescribed minimum economic profit per head of livestock (Iranian Rial), respectively.

The non-negativity constraint requires that the decision variables must not take negative values, as presented in Eq. 14 (Li et al., 2020).

$$N_l \geq 0 \quad \forall \ l \qquad (14)$$

Fig. 1 Minimum and maximum production of animal manure
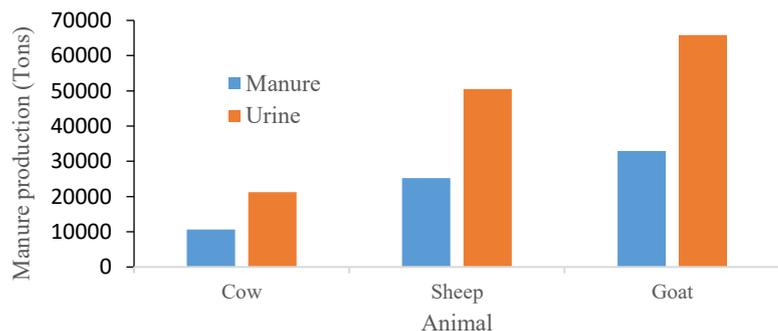
where, l, pl, manu and uri denote the indices for livestock, livestock-emitted pollution, solid manure, and liquid manure, respectively. The framework developed in this study is highly comprehensive, integrating natural, social, economic, and environmental dimensions. It involves a wide range of input parameters, including those related to various livestock types, biomass energy production and economic indicators, pollutant emissions, fixed parameters, and others. Data were collected from the Kerman Provincial Agriculture Organization and the Kerman Regional Water Authority, and supplemented by relevant international studies (Su et al., 2017; Li et al., 2020). The dataset covers the agricultural years 2015–2022. Since the model inputs are defined as intervals, the input data were duplicated to determine the minimum and maximum values of the objective functions. For the second objective function, which aims to minimize environmental impacts, nondimensionalization is required prior to solving the model, as greenhouse gas emissions and water and soil pollutants are expressed in different units. To achieve the research objectives, a hybrid solution framework combining Monte Carlo simulation with an evolutionary genetic algorithm was employed.

3. Results and Discussion

Since pastoralism and livestock farming represent one of the primary sources of income in this county, the region generates a substantial amount of livestock waste, which can lead to severe air and water pollution. Livestock waste possesses significant potential for biomass energy production, which in turn can enhance livestock productivity, reduce water and soil pollution, lower greenhouse gas emissions, and contribute to a sustainable circular economy. This approach also aligns with government policies promoting the transformation of "waste into wealth" and the development of "beautiful cities."

3.1 Livestock manure production calculation

The amount of manure produced by an animal depends on several factors, including body weight, size, age, feed intake, and animal type (Avcıoğlu and Türker, 2016). Regional data indicate that, on average, each cow produces between 14.45 and 14.78 kg of manure per day. Sheep and goats generate, on average, 1.34–1.39 kg and 1.20–1.26 kg of manure per day, respectively. Other livestock, such as camels, donkeys, horses, and poultry, are also present in the region but were excluded from the study due to their low numbers. The amount of urine produced by cows, sheep, and goats was estimated to be approximately 50% of their fecal output, which is consistent with the findings of Li et al. (2020). Minimum and maximum production of animal manure are shown in Fig. 1.

3.2 Calculation of biomass energy potential from livestock manure

Biomass energy production is a form of clean and renewable energy, accessible to everyone, and it also minimizes environmental pollution. Second-generation biomass energy production from livestock manure is available in the Orzuieh region. In this study, biogas production from animal manure was influenced by several factors, including livestock numbers, manure emission quantities, manure collection efficiency, dry matter content, biogas yield per unit of dry matter, the thermal energy ratio of livestock manure to coal, and the calorific value of coal. The model estimation was performed using Monte Carlo simulation combined with a genetic algorithm, and the minimum and maximum biogas production in the region were estimated at 1.24×10^8 MJ and 3.07×10^8 MJ, respectively. The results of this section are consistent with the findings of Li et al. (2020) and Oliveira et al. (2021), as these studies indicated that livestock manure is an important source for biogas or biomethane production and that biogas generation reduces greenhouse gas emissions. Furthermore, Oliveira et al. (2021) reported that a significant portion of rural electricity consumption in the state could be supported by these new investments, thereby enhancing energy security and reliability in meeting energy demand. The annual biogas production per animal is illustrated in Fig. 2.

Fig.2 illustrates the total annual biomass energy production per animal. Biomass energy production is positively correlated with livestock numbers. Goats contribute the most to biomass energy production, whereas cows contribute the least. Small ruminants in the region hold greater significance and

population compared to large livestock, as they primarily graze on pastures and pose lower risks relative to large animals.
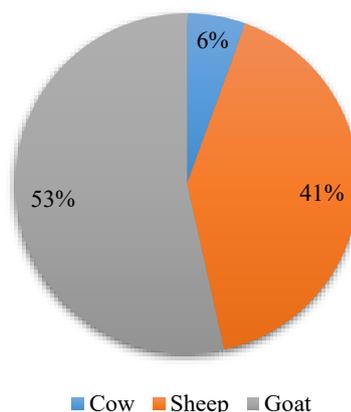

Fig. 2 Biomass energy production by each livestock

3.3 Sustainability of bioenergy production

If the objective were solely to maximize bioenergy production, it would result in higher costs, increased land pollution, and elevated greenhouse gas emissions. Therefore, this study accounted for both economic and environmental impacts when optimizing bioenergy production. Consequently, the model simultaneously optimized three objective functions, capturing the trade-offs among conflicting objectives within the WEFN framework. This outcome aligns with Li et al. (2020), indicating that the optimization model tends to produce strategies that achieve cost efficiency and environmental protection while mitigating air and water pollution within the context of nexus-based approaches.

Table 1 Estimation of research objective functions

Bioenergy production (MJ)		Cost (IRR)		Environmental impact (kg)	
Min	Max	Min	Max	Min	Max
1.24×10^8	3.07×10^8	4.62×10^{13}	2.54×10^{14}	5.16×10^7	7.12×10^7

3.4 Costs and environmental impacts of bioenergy production

The environmental impacts of the region were considered under conditions of biomass energy production to assess the pollution resulting from livestock activities. According to the model results, the minimum and maximum emissions of air and water pollutants from livestock activities in the region range from 5.16×10^7 kg to 7.12×10^7 kg for the entire area. Methane from the livestock sector represents the largest share of greenhouse gas emissions. Methane and nitrous oxide release 21 and 310 times more heating energy, respectively, compared to carbon dioxide, making them significantly more potent contributors to local and global climate change. Cows have the highest contribution to greenhouse gas emissions, producing up to 79 kg of methane per year, while sheep and goats produce a maximum of 5.28 kg and 5.26 kg of methane, respectively. Livestock not only contribute substantially to global warming through greenhouse gas emissions but also act as major sources of water and soil pollution. Overall, livestock farming has a considerable impact on both global warming and environmental pollution. Dillon et al. (2021) reported that

manure management and enteric fermentation account for approximately 41% of agricultural sector greenhouse gas emissions. Livestock contribute nearly 14.5% of total greenhouse gases, a proportion comparable to that of the transport industry (Patra, 2013). Aan den Toorn et al. (2020) highlighted that cows contribute more to greenhouse gas emissions, particularly methane, than other food-producing animals, corroborating the findings of this study. Su et al. (2017) also demonstrated that among food-producing livestock such as cows, sheep, goats, and pigs, cows produce the highest methane emissions and water pollution. Consequently, previous studies support the results of this research. Fig. 3 illustrates the annual environmental pollution caused by each type of livestock. Although goats, due to their larger population, contribute more to total pollution, they produce 1.49×10^6 kg of pollutants with a population 36 times larger than cows, whereas 3,933 cows generate approximately 65% of the pollution produced by goats.

From an environmental standpoint, cows are responsible for relatively higher air pollution compared to sheep and goats. Numerous studies have explored strategies to mitigate enteric

methane emissions from ruminants. It is well established that dietary management plays a crucial role in regulating methane release in dairy cattle (Lassen et al., 2012). Specific nutritional interventions can reduce methane emissions by influencing feed conversion efficiency and methane output per kilogram of product (Garnsworthy et al., 2019).

Fig. 3 The amount of greenhouse gas emissions and water pollution from livestock
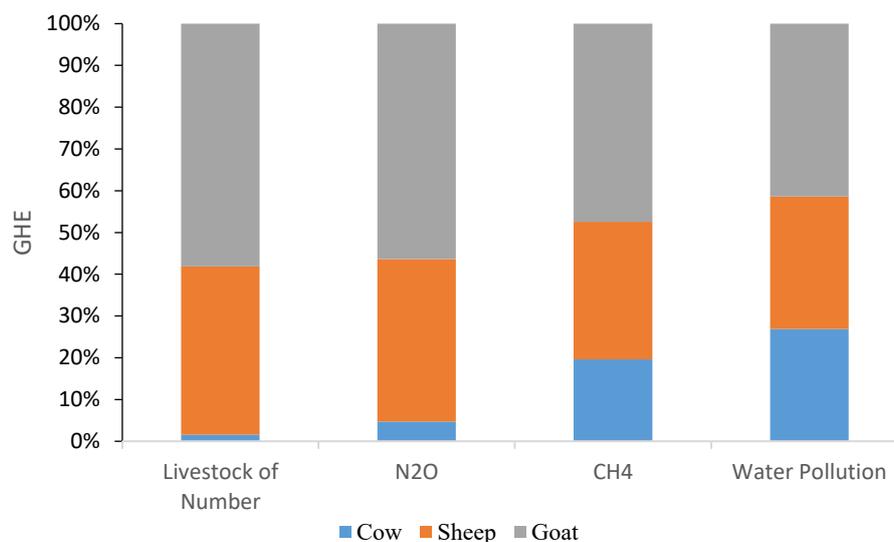
Approaches such as lowering the forage-to-concentrate ratio, modifying rumen microbial populations, or increasing dietary lipid content have all been proposed as effective strategies for methane mitigation (Cottle et al., 2015). Under controlled laboratory conditions, Kinley et al. (2016) demonstrated that dietary inclusion of algae nearly completely suppressed methane production without compromising forage digestibility.

The third objective of the model focused on livestock production costs, with the minimum and maximum values of the cost function estimated at 4.62×10^{13}, and 2.54×10^{14} IRR, respectively. In the region, small ruminants predominantly graze on natural pastures, whereas large livestock rely mainly on cultivated croplands. The coexistence of agriculture and pasturelands helps mitigate overall livestock farming costs. Nonetheless, feed price increases over the five years, driven by inflation, indicate a 450% surge. Such substantial cost escalation could inflict irreparable damage on the sustainable development trajectory of regional livestock farming.

3.5 Applications and potential of biomass energy

Biomass energy has diverse applications, including bioethanol production (fuel, healthcare, industrial uses), electricity generation, and natural gas production. Model results indicate that approximately 1.37×10^8 kg of manure is produced annually, capable of generating around 3.07×10^8 MJ of bioenergy, equivalent to 3.8×10^7 m³ of natural gas. Animal manure represents a promising renewable energy source for biomass energy exploitation, serving as a clean energy option for environmental sustainability. Anaerobic digestion can add value to manure while reducing environmental impact, contributing significantly to agricultural systems and public health improvement (Roubík et al., 2017; Afi Seglah et al., 2022). Balaman (2016) reported that anaerobic digestion reduces livestock waste pollution and produces high-quality fertilizer suitable for agricultural use.

Bijarchiyan et al. (2020) developed a model for sustainable biomass production using anaerobic digestion technology applied to livestock and agricultural residues through an optimization framework. Their study indicated that biogas production from three plants in the Gonbad Kavous region, with an annual capacity of 1,000 tons of manure, could supply electricity to 101,556 households per month. HassanzadehFard et al. (2022) demonstrated that utilizing energy generated from various waste types plays a significant role in conserving fossil fuels and mitigating fossil fuel depletion. According to their findings, the utilization of all available waste could reduce natural gas consumption by approximately 17.46%. Furthermore, assuming 100% availability of animal manure, natural gas consumption could decrease from 2.373 million liters to 1.60 million liters, representing a 32.35% reduction. Both studies (Bijarchiyan et al., 2020; HassanzadehFard et al., 2022) indicate that biogas production from livestock waste reduces fossil fuel consumption and, by substituting green fuels and preventing environmental discharge of waste, mitigates greenhouse gas emissions and water and soil pollution. These results corroborate the findings of the present study. Moreover, Zarrinpoor (2023) reported that biomass energy production substantially enhances regional environmental and social objectives, further supporting the positive impacts of converting livestock and agricultural residues into energy, consistent with the outcomes of the current research.

4. Conclusion

Today, mitigating global warming and environmental pollution requires reducing fossil fuel consumption and substituting green energy sources. Although various renewable energy forms, such as wind, solar, and nuclear, are utilized worldwide, they are not universally accessible. In contrast, biomass energy represents a widely available and environmentally friendly option that can be produced from livestock waste, agricultural residues (both crop and orchard), human waste, industrial waste, municipal solid waste, and

other sources. The utilization of biomass energy contributes to the reduction of greenhouse gas emissions and mitigates environmental pollution.

1. The findings of this study provide an empirical basis for estimating the economic and environmental impacts of biomass energy production. Livestock manure in the Arzuiyeh region possesses substantial potential for generating annual biomass energy equivalent to approximately 3.8×10^7 m³ of natural gas. Unlike fossil fuels, this renewable energy source is environmentally friendly and requires comprehensive political, financial, and cultural support from governments. Policymakers and regulatory authorities should establish a legal framework to promote clean fuels, reduce greenhouse gas emissions, and facilitate investment and participation in biofuel production.

2. Livestock, while producing food, are major contributors to methane emissions and water and soil pollution. Among livestock, cattle contribute disproportionately to greenhouse gas emissions and environmental pollution.

3. The methodology and approach of this study provide a framework for other predominantly livestock-based regions with inefficient manure management to generate biomass energy.

Future studies should aim to expand this approach to larger scales and incorporate additional feedstocks, such as crop and orchard residues, slaughterhouse waste, and others. Moreover, the trade-offs among various agricultural waste applications, bioenergy processing, and additional sources of uncertainty should be considered to enhance the practical applicability of the modeling framework under real-world conditions.

Statements and Declarations
Acknowledgments

Data availability

The data can be sent by email upon request to the corresponding author.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

Sh. Mousapour: Investigation, Methodology, Data Curation, Formal Analysis, Visualization, Resources, and Writing – Original Draft; M. Hashamitabar: Data Curation, Formal Analysis, Resources, Supervision, and Writing – Review & Editing; M. Safdari: Methodology, Formal Analysis, Supervision, and Writing – Review & Editing. A. Sardar-Shahraki: Validation, Formal Analysis, Supervision, and Writing – Review & Editing.

AI Use Declaration

During the preparation of this work, the author(s) used ChatGPT to improve some sentences. The authors have thoroughly reviewed and revised the content as necessary and assumed full responsibility for the final manuscript.

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