Front. Agr. Sci. Eng. 2024, 11(3): 381–396
https://doi.org/10.15302/J-FASE-2024552

RESEARCH ARTICLE

Spatiotemporal distribution, environmental risk and carbon emission reduction potential of livestock manure in Shaanxi Province, China

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KEYWORDS

Livestock manure, emission estimation, N and P loads, biogas potential, carbon emission reduction

HIGHLIGHTS

- Production, distributions and environmental risks of LM in Shaanxi were studied.
- Energy utilization and carbon emission reduction potentials of LM in Shaanxi were estimated.
- LM in Shaanxi reached 4.64×10^6 t in 2021 with cattle and pig manure as the primary sources.
- LM is concentrated in northern Shaanxi and the eastern part of Hanzhong.
- Volumes of LM in Ankang and Hanzhong posed potential N and P pollution risks.
- LM energy potential and carbon emission reduction potential are 1.2×10^{11} MJ and 22%.

Received August 31, 2023;
Accepted January 29, 2024.

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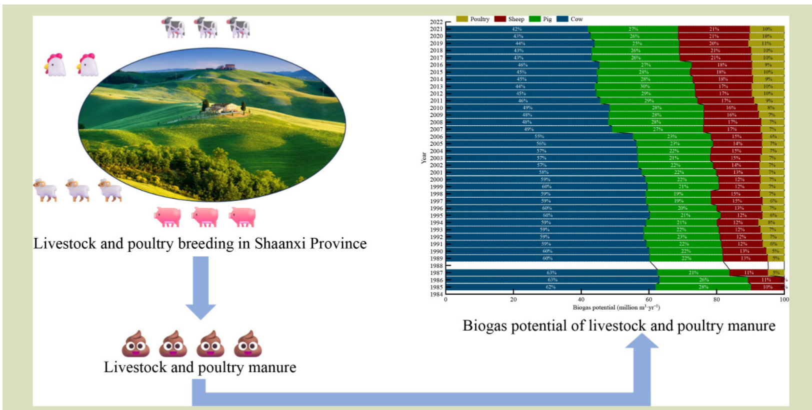
GRAPHICAL ABSTRACT



ABSTRACT

Shaanxi is a leading province in animal husbandry (AH) in China. However, the lack of provincial information on the characteristics and utilization potential of livestock manure (LM) hinders crucial management decisions. Therefore, we investigated the spatiotemporal distribution, availability and biogas potential of LM in Shaanxi, and examine the carbon emission reduction potential of AH. There has been a 1.26-fold increase in LM quantities in Shaanxi over the past 35 years, reaching 4635.6×10^4 t by 2021. LM was mainly concentrated in northern Shaanxi and the eastern part of Hanzhong. Cattle and pig manure were the primary sources of LM, with the average LM land-load of 14.57 t·ha^{-1} in 2021. While the overall AH in Shaanxi has not exceeded the environmental capacity, the actual scales of AH in Ankang and Hanzhong have already surpassed the respective environmental capacities, posing a higher risk of N and P pollutions. In 2021, the estimated biogas energy potential of LM was 1.2×10^{11} MJ. From 2012 to 2021, the average carbon emission reduction potential in Shaanxi was 22%, with an average potential scale of 10%. The results of this research provide valuable data and policy recommendations for promoting the intensive use of LM and reducing carbon emissions in Shaanxi.

1 Introduction

Animal husbandry plays a crucial role in the rural socioeconomic development of developing countries[1]. It provides income and employment opportunities for producers, and stimulates the development of upstream and downstream industries[2]. As a developing country, China has experienced an increase in living standards and a growing demand for meat, eggs, and dairy products with its economic growth. China is the world's largest consumer and producer of meat, accounting for over 30% of global meat production[3]. However, with the continuous expansion of animal husbandry, the proper management of livestock manure (LM) becomes a paramount agenda for sustainability. In 2017, the wastewater discharged from livestock and poultry farms contained 3.7×10^5 t of total nitrogen (N) and 8.04×10^4 t of total phosphorus (P), accounting for 12.16% and 25.49% of the total N and P discharged from various types of wastewater in the country[4]. LM has become an obvious source of water pollution. Exploring ways to effectively utilize LM while reducing environmental pollution is an urgent problem that needs to be solved[5–9].

At present, there are numerous studies on the production of biogas by anaerobic digestion of LM and the preparation of organic fertilizer by aerobic composting[10]. However, it is crucial to investigate the availability and distribution patterns of LM to promote biogas engineering[11]. This highlights China's attention to LM utilization[12]. Recently, some researchers have begun to address this issue by concentrating on the regional availability and distribution patterns of LM. For example, Hu et al.[13] calculated the carbon emissions and distribution patterns of agriculture in Jiangsu province. Wu et al.[14] analyzed the spatial distribution of LM and the environmental pollution caused by LM in Anhui province. Wang et al.[15] evaluated the distribution patterns of LM in multi-ethnic areas of China. These investigations provided practical recommendations for regional development and management of LM. However, most of these investigations are focused on small regions in the eastern part of China. Research related to the north-west part of China, including Shaanxi province, is limited. In addition, many studies evaluated the availability and distribution patterns of LM over a relatively short time span, typically three or five years. A comprehensive understanding of the development of animal husbandry as well as the spatiotemporal distribution of LM is still needed, considering the push for sustainability of animal husbandry and the dynamic selection of LM management strategies in specific areas. Moreover, a systematic analysis of the availability, spatiotemporal distribution, environmental risks, carbon emission reduction potential, as well as the production and energy potentials of LM is urgently needed for better LM management. Addressing these issues across different provinces will promote the efficient utilization of LM with scientifically sound and reasonable methods[9].

Shaanxi is province, which can represent the development of livestock and poultry industry in western China. Promoting the utilization of LM in Shaanxi is fundamental to greening its livestock and poultry industry and that of the entire western China. By the end of 2020, the stock of pigs, cattle and sheep manure in Shaanxi Province reached 8.5 million, 1.5 million, and 8.7 million barrels, respectively[16]. However, there is currently a lack of information, such as the characteristics of LM resources, for decision-making in environmental management. This study estimated the temporal variation of LM production in Shaanxi Province from 1985 to 2021, analyzed the spatial variation of LM in 2021, assessed the cultivated land load and environmental risks of LM, and estimated the potentials of energy utilization and carbon emission reduction of LM. It not only provides comprehensive information for utilization of livestock and poultry manure, but also offers feasible suggestions for optimizing relevant policies.

2 Materials and methods

2.1 Research area overview and data sources

Shaanxi Province, situated in the inland heartland of China, is located between east longitudes 105°29′–111°15′ and north latitudes 31°42′–39°35′. In 2020, there were a total of ten cities in Shaanxi Province comprising Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Hanzhong, Yulin, Ankang, and Shangluo. The province also houses the Yangling High-tech Agricultural Industry Demonstration Zone. Based on geographical and cultural differences, Shaanxi Province is divided into three main regions: Northern Shaanxi, Southern Shaanxi, and Guanzhong Area. The Northern Shaanxi region primarily includes Yan'an and Yulin cities. Southern Shaanxi encompasses Hanzhong, Ankang, and Shangluo cities. The Guanzhong Area comprises Baoji, Weinan, Xianyang, Tongchuan, and Xi'an cities. With an area of 2.06×10^5 km^2 and a population of about 4.0×10^7, accelerating the development of animal husbandry is significant for promoting the modernization of agriculture in Shaanxi Province[17].

The data used in this study were sourced from the Shaanxi Statistical Yearbook 1986–2022 and China Animal Husbandry and Veterinary Yearbook 2022[16]. The Yangling High-tech Agricultural Industry Demonstration Zone was established in 1997, therefore, data before 1997 were not available for the area. For the ease of calculation, the data for the Yangling High-tech Agricultural Industry Demonstration Zone was combined with that of Xianyang city since it is under the jurisdiction of the city. The cultivated land areas of Shaanxi Province and various regions therein were extracted from the Shaanxi Statistical Yearbook 2022[17]. Using the livestock and poultry breeding data from 1985 to 2021, this study calculated the LM production by cattle, sheep, poultry and pigs in each city. It estimated the N and P produced from animal husbandry and calculated the N and P loads of arable land in Shaanxi Province. This study also predicted the biogas potentials and carbon emission reduction potentials of LM in Shaanxi Province.

2.2 Estimation methods

The statistical yearbooks do not provide specific data on beef cattle, dairy cows, and work cattle. Therefore, they were all treated as cattle in the estimation. Similarly, there is no distinction made between goats and sheep, and they were all grouped as sheep in this study. Broilers, hens, geese, and ducks are not differentiated in the yearbooks, and they were classified as poultry.

2.2.1 LM production calculation

The amount of LM is typically estimated using the excretion coefficient method. This method calculates the weight of various types of livestock and poultry manure based on the number of livestock and poultry, the feeding cycle, and the excretion coefficient[6,11]. Alternatively, it can also be calculated using the ratio of the weight of a particular type of livestock and poultry to the amount of manure produced[3]. With reference to a study by Khoshnevisan et al.[18], the amount of LM in Shaanxi Province from 1985 to 2021 was estimated using Eq. (1).

$$M = W \times R_{manure} \quad (1)$$

where M, W and R_{manure} are the total amount of manure (kg), the weight of the animal (kg), and the ratio of manure production to weight, respectively. Based on the actual agricultural scene in Shaanxi Province, we assumed that the average weights of individual cattle, pig, sheep, and chicken were 250, 100, 80, and 1.5 kg, respectively. The ratios of manure production to weight for cattle, pig, sheep, and poultry were calculated as 10%, 4%, 4%, and 3%[19], respectively.

2.2.2 Biogas potential of LM

LM can be used for bioenergy production. Different types of LM have different contents of total solid (TS), and thus, different biogas conversion efficiencies. Here, the theoretical biogas potential of LM from 1985 to 2021 was calculated for Shaanxi Province using the equation recommended by Abdeshahian et al.[20].

$$TPB = M \times TS \times EB_{TS} \quad (2)$$

where TPB is the theoretical biogas potential (m^3·yr^{-1}), M is the total amount of manure, TS is the percent of total solids in animal manure (i.e., 25% for cattle, pig, and sheep, and 29% for poultry). EB_{TS} is the estimated quantity of biogas produced per kilogram of TS (i.e., 0.4 for pig and sheep, 0.6 for cattle, and 0.8 for poultry) (m^3·kg^{-1} TS).

The energy potential of biogas depends on its methane (CH_4) content. The optimal anaerobic digestion temperature is 35 °C[21]. Some studies revealed that the average contents of CH_4 in biogas produced from manure are 64% for cattle, 60% for pig and sheep, and 70% for poultry[22,23]. The energy potential for each type of manure (E_{biogas}) was calculated with Eq. (3).

$$E_{biogas} = Q_{biogas} \times \omega \times CV_{CH_4} \quad (3)$$

where Q_{biogas} is the quantity of biogas produced; ω is methane content (%); and CV_{CH_4} is the combustion value (40 MJ·m^{-3}) of CH_4[24].

2.2.3 Estimation of N and P contents in LM

N and P are the main nutrients in LM, which can increase crop yield and improve soil fertility. However, in excessive amounts, they will cause crop quality reduction and soil pollution[25]. The total N and P in LM is calculated with Eq. (4).

$$\mathrm{TN(TP)} = S_i \times W_i \times E_i \tag{4}$$

where TN(TP) is the total N(P); i is the i th type of livestock and poultry; S is the number of livestock and poultry farmed; W is the feeding cycle (d); E is the daily N and P excretion coefficients of livestock and poultry ($\mathrm{g{\cdot}d^{-1}}$). The daily N and P excretion coefficients of various livestock and poultry in Shaanxi Province were taken from the literature and listed in Table 1. The average feeding cycles are 199 d for pig, 365 d for cattle and sheep, and 210 d for poultry.

2.2.4 Theoretical loading rate of LM on farmland

The nutrient profiles of different types of LM vary greatly, leading to substantial differences in their application or usage on farmland. When the load of LM per unit area is calculated by taking into account the different types of LM, the actual impact may differ even if the loading quantity remains the same[26–28]. With reference to the specific N contents of various types of LM in Shaanxi Province, cow manure, poultry and sheep manure were uniformly converted into pig manure equivalents. Therefore, the loading of LM on arable land was calculated using pig manure equivalents. The conversion coefficients for cow manure, poultry and sheep manure are shown in Table 2. The LM load of arable land was calculated using Eq. (5).

$$q = Q/H = \sum X \times T/H \tag{5}$$

where q is LM load of arable land ($\mathrm{t{\cdot}ha^{-1}}$); Q is the pig manure equivalent of LM; H is the area of arable land (ha); X is the amount of LM (t); T is the conversion coefficient of cow manure, poultry manure, sheep manure or pig manure.

2.2.5 Threshold LM load for arable land

Based on the recommendation of the Chinese government, the maximum suitable load of organic fertilizer on farmland is 30 $\mathrm{t{\cdot}ha^{-1}}$. The threshold value of LM load was quantified with Eq. (6) and assessment was conducted using Table 3[28].

$$R = q/p \tag{6}$$

where R is the threshold value of LM load of arable land; q is LM load of arable land ($\mathrm{t{\cdot}ha^{-1}}$); p is the maximum load of LM per unit area of arable land (30 $\mathrm{t{\cdot}ha^{-1}}$).

The threshold values of LM are divided into six levels as shown in Table 3. The higher the levels, the more serious the threat of pollution posed by LM.

Table 1 Breeding days and the contents of N and P in the manure of livestock and poultry in Shaanxi Province

Item	Cow manure	Pig manure	Sheep manure	Poultry manure
Breeding cycle (d)	365	199	365	210
Nutrient in manure ($\mathrm{g{\cdot}d^{-1}}$)				
N	144.995	31.73	2.15	1.485
P	14.045	4.22	0.46	0.335

Table 2 Conversion coefficients of the manure of livestock and poultry

Item	Cow manure	Cow namure	Sheep manure	Poultry manure
Nitrogen content	0.78	0.65	0.8	1.37
Pig manure equivalent conversion coefficients	1.2	1	1.23	2.1

Table 3 Classification of LM threshold values

Item	Threshold value (R)					
	< 0.4	[0.4,0.7)	[0.7,1.0)	[1.0,1.5)	[1.5,2.5)	⩾2.5
Classification	I	II	III	IV	V	VI
Threats to the environment	No	Low	Moderate	High	Severe	Critical

2.2.6 LM-related N and P loads of farmland and environmental risk assessment

Currently, the primary method of treating LM is to use it as organic fertilizer. When calculating the N and P loads of arable land due to LM application, the arable land area in Shaanxi Province in 2021 was used as the actual load area. The arable land area of each city in Shaanxi Province was obtained from the *Shaanxi Statistical Yearbook 2022*. The LM-related N and P loads of arable land was calculated with Eq. (7).

$$t = F/S \tag{7}$$

where t (kg·ha^{-1}) is the environment loads of N and P from LM; F is the N and P contents of LM (kg), and S is the effective arable land area (ha). The quantitative index of LM-related N and P loads per unit of arable land can be used to indirectly measure the pollution caused by LM in Shaanxi[29]. The total N (P) emissions of different livestock and poultry were converted into pig manure equivalents, and the N and P carrying capacities of arable land were used to calculate the environmental capacity as Eqs. (8)–(10).

$$\mathrm{T_{N/P}} = \mathrm{A} \times \mathrm{C_{N/P}} \tag{8}$$

$$\mathrm{PN} = \mathrm{T_{N/P}}/d \tag{9}$$

$$\mathrm{R_N} = \sum\nolimits_i^n \mathrm{TN(P)}_i/d \tag{10}$$

Where $\mathrm{T_{N/P}}$ is the total N(P) environmental capacity of arable land and pastureland (10^4 t); A is the total area of arable land and pastureland (ha); $\mathrm{C_{N/P}}$ is the annual N(P) limit for manure fertilizer based on the specific conditions of Shaanxi Province, with $\mathrm{C_N} = 170\ \text{kg·ha}^{-1}$, $\mathrm{C_P} = 35\ \text{kg·ha}^{-1}$[30]; $\mathrm{P_N}$ is the environmental capacity of animal husbandry (10^4 pig equivalent); d is the total N(P) annual emissions of a pig (t); $\mathrm{R_N}$ is the actual scale of animal husbandry (10^4 pig equivalent); $\mathrm{TN(P)}_i$ is the total annual N(P) emissions of animal husbandry (t).

2.2.7 Calculation of carbon emission reduction potential of LM in Shaanxi Province

Carbon emissions from livestock production mainly come from the enteric fermentation of ruminant animals, leading to CH_4 and N_2O emissions from manure. Due to the different chemical properties of CH_4, N_2O, and carbon (C), it is difficult to directly use them for the calculation of carbon emissions. Therefore, this study adopted the conversion factors recommended by IPCC (1 t CH_4 = 6.68 t C, 1 t N_2O = 81.27 t C) to convert CH_4 and N_2O into carbon equivalents[31]. The main carbon sources and carbon emission coefficients are presented in Table 4. Additionally, a more comprehensive non-radial model called the Slack-Based Measure (SBM) model (Eq. (11)) was employed. It introduced slack variables in the objective function to effectively compensate for the limitations caused by the presence of slack variables and reduce the resulting errors[33].

$$E^* = \min \frac{1 - \dfrac{1}{k}\sum\limits_{i=1}^{k}\dfrac{z_i^-}{x_{i0}}}{1 + \dfrac{1}{k_1+k_2}\left(\sum\limits_{r=1}^{k_1}\dfrac{z_r^g}{y_{r0}^g} + \sum\limits_{r=1}^{k_2}\dfrac{z_r^c}{y_{r0}^c}\right)}, \ s.t. \begin{cases} x_0 = \lambda X + Z^- \\ y_0^g = \lambda y - Z^g \\ y_0^c = \lambda y^c - Z^c \\ z^-, z^g, z^c, \lambda \geqslant 0 \end{cases} \tag{11}$$

where x, y, c, z^-,z^g, z^c, and λ are input factors, desired outputs, undesired outputs, input slack variables, desired output slack variables, undesired output slack variables, and weights, respectively. When $z^- = z^g = z^c = 0$, the decision unit is considered fully efficient ($E^* = 1$). Descriptions of the input-output indicators are presented in Table 5. The potential for carbon emission reduction of animal husbandry in Shaanxi Province from 2012 to 2021 was estimated by employing the SBM model. Eqs. (12) and (13) show the formula of the SBM model.

$$\mathrm{PAC}_t = \frac{\mathrm{AC}_t - \mathrm{BC}_t}{\mathrm{AC}_t} \tag{12}$$

$$\mathrm{SCE}_t = \frac{\mathrm{AC}_t - \mathrm{BC}_t}{\sum\limits_{s=1}^{10}(\mathrm{AC}_t - \mathrm{BC}_t)} \tag{13}$$

where PAC_t is the carbon reduction potential of animal husbandry; SCE_t is the potential scale of carbon reduction; AC_t is the actual carbon emissions from animal husbandry in the

Table 4 CH_4 and N_2O emission coefficients of livestock and poultry[32]

Types	Enteric fermentation	Fecal discharge	
	CH_4/(kg·(head·yr)$^{-1}$)	CH_4/(kg·(head·yr)$^{-1}$)	N_2O/(kg·(head·yr)$^{-1}$)
Cow	47	1	1.39
Sheep	5	0.16	0.86
Pig	1	4	0.35
Poultry	–	0.02	0.02

Table 5 Description of input and output indicators

Category	Index	Description
Input variables (x)	Land (10^3 ha)	Arable land
	Livestock breeding capital (10^8 yuan)	Fixed investments of animal husbandry
	Labor (10^4)	Employees of animal husbandry
Expected output (y)	Gross value of animal husbandry production (10^8 yuan)	Gross value of livestock and poultry productions
Undesired output (c)	Carbon emissions of animal husbandry (10^4 t)	Carbon emissions of animal husbandry in Shaanxi Province

tth year in Shaanxi Province; and BC_t is the optimal carbon emissions in the tth year in Shaanxi Province. All the data were retrieved from the Shaanxi Statistical Yearbook[17].

3 Results

3.1 Temporal Distribution of LM in Shaanxi Province from 1985 to 2021

The total amount of LM in Shaanxi Province showed an upward trend from 3674.1 × 10^4 t in 1985 to 5918 × 10^4 t in 1996 (Fig. 1). This increase can be attributed to the rapid development of China's animal husbandry after 1978, which was propelled by national policies, such as regulating the market prices of livestock and poultry, reducing the control of agricultural products, and promoting the development of animal breeding[34,35]. In 1997, the production of LM in Shaanxi Province decreased to 4691.2 × 10^4 t, indicating a decline in the breeding volume of various types of livestock and poultry. In the late 1990s, the government implemented a series of policies to optimize and adjust the structure of the livestock industry and improve the quality of livestock products[36]. From 1997 to 2006, the amount of LM in Shaanxi Province increased steadily, from 4691.2 × 10^4 t in 1997 to 7070.1 × 10^4 t in 2006, reaching its maximum output in the 20th century. The average annual output of LM during this period was 5846.8 × 10^4 t. During this period, the Shaanxi Province government implemented a series of policies aimed at enhancing the quality and efficiency of livestock and poultry breeding. These measures had a positive impact on enriching the residents' "vegetable basket" and elevating farmers' economic well-being,

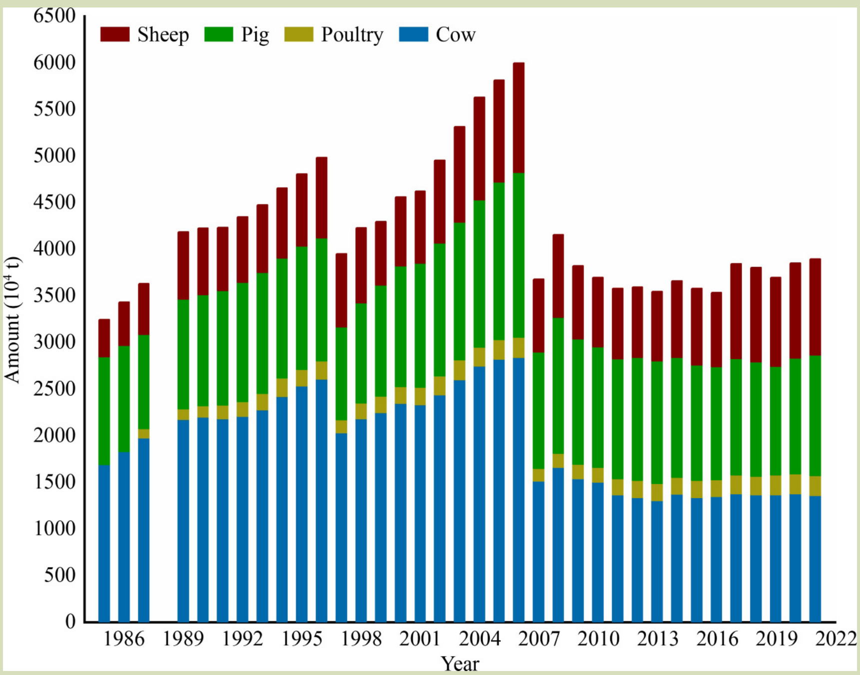


Fig. 1 The amount of LM in Shaanxi Province from 1985 to 2021.

thereby contributing to overall societal development[37,38]. In 2007, there was a notable decline in the production of LM in Shaanxi Province, reaching a mere 4311 × 10^4 t. This was primarily attributed to the low market price of live pigs, elevated feed costs, and the adverse effects of epidemic diseases, particularly the Porcine Reproductive and Respiratory Syndrome, and avian influenza, that significantly impacted pig breeding[36,39]. Additionally, around 2006, the livestock industry in China experienced an overall decline in prices, coinciding with a crucial phase of structural reform. The ongoing optimization of production structure played a significant role in triggering a decline in pig production and a supply surplus within the industry[40]. This phenomenon signified a turning point in the trajectory of China's livestock sector. The reduction of poultry farming and continuous decline in the price of livestock products dampened pig farmers' enthusiasm for production. Thereafter, livestock and poultry farming in Shaanxi Province remained relatively stable, indicating the significant impact of policy adjustments. To illustrate the variation in the sources of LM in Shaanxi Province from 1985 to 2021, the pig manure equivalent of LM in Shaanxi Province was calculated, and the result is depicted in Fig. 2. It is evident that cow manure constituted the primary source of LM in Shaanxi Province, accounting for 35.3% to 55.3% of the total annual production, with an average contribution of 46.5%. Following closely was pig manure, with a contribution ranging from 21.1% to 31.4%, and an average contribution of 26.2%. On the other hand, the production of sheep manure and poultry manure remained relatively modest, contributing to 13.3% to 36.9% of the total respectively, with an average contribution of 27.3%. The profound influence of cow manure on the overall quantity of livestock and poultry manure in Shaanxi Province was noteworthy, followed by pig manure. The annual outputs of these two types of manure directly determined the availability and fate of LM in the region, which aligns with the findings of other scholars[41,42].

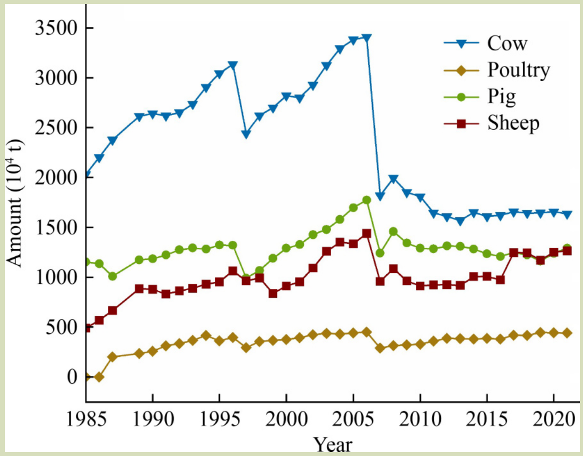


Fig. 2 Pig manure equivalent of LM in Shaanxi Province in 1985–2021.

3.2 Spatial distribution of LM in Shaanxi Province in 2021

In 2021, the regions with relatively higher LM production in Shaanxi Province were primarily concentrated in the western and northern parts, particularly in the northern part of Shaanxi

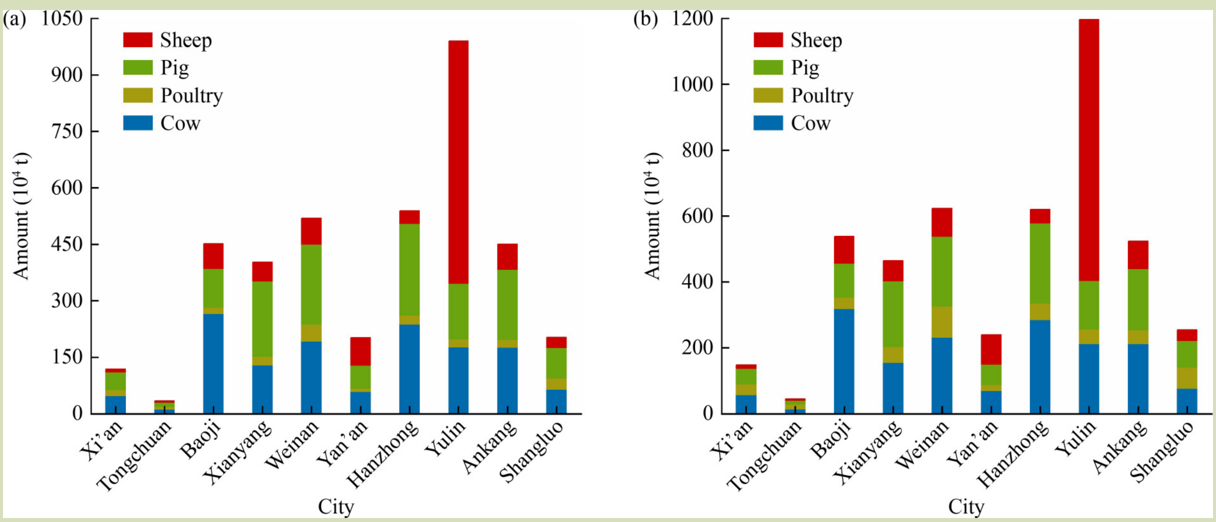


Fig. 3 (a) Amount of LM; (b) amount of LM as pig manure equivalent.

and the eastern part of Guanzhong (Fig. 3). The areas in Shaanxi Province where LM production exceeded 4 million tons included Yulin in the northern part of Shaanxi at 11.79 million tons (26.3%); Hanzhong city at 6 million tons (13.4%), Weinan city at 5.9 million tons (13.1%), Baoji city in the western part of Guanzhong area at 5.2 million tons (11.7%), and Ankang city at 5.1 million tons (11.3%). The regions with manure production ranging from 2 million to 4 million tons mainly included Shangluo city (2.3 million tons; 5.1%) and Yan'an city (2.3 million tons; 5.1%). Tongchuan city had the lowest production of 0.4 million tons (0.9%).

In addition, the average LM load of arable land in Shaanxi Province was 14.57 t·ha^{-1} (Table 6), which was significantly lower than the limit of 30 t·ha^{-1}, indicating a strong potential for farmland use of LM in Shaanxi Province. However, there were significant variations in LM load of arable land in different regions of Shaanxi Province. For example, regions with higher LM loads were primarily concentrated in the western part of Guanzhong area and the south-western part of Shaanxi. Regions with lower LM loads mainly comprised Xi'an city and Weinan city, because these cities are located in the plain region with adequate capacity for acceptance of LM. Hanzhong city and Ankang city had relatively higher LM loads, with the load rates of 23.8 and 22.8 t·ha^{-1}, respectively, as they are located in mountainous areas with low capacity for farming. Arable land in other cities had LM loads in the range of 14.5–17.4 t·ha^{-1}.

In 2021, R-values of the pollution risk indices of LM in various cities of Shaanxi Province ranged from 0.2 to 0.8 (Table 6). Among the cities, Ankang city and Hanzhong city exhibited relatively higher environmental risk with R-values reaching a warning level of 0.8, indicating that the amount of LM produced in these areas had exceeded the carrying capacity of the farmland. The region with the lowest R-value was Xi'an city, which is the provincial capital with a relatively high level of economic development, and where most meat products were imported. Although, the LM load of arable land in Shaanxi Province was relatively low, with an average R-value of 0.49, environmental protection in areas such as Ankang city and Hanzhong city should not be overlooked.

3.3 LM-related N and P loads of arable land in Shaanxi Province in 2021

The output of N from animal husbandry in Shaanxi Province showed a tortuous upward trend, increasing from 15.1 × 10^4 t in 1985 to 16.6 × 10^4 t in 2021, with the highest N output of 27.4 × 10^4 t occurring in 2006 (Fig. 4(a)). Similarly, the output of P from animal husbandry in Shaanxi Province also showed an increasing trend, rising from 1.7 × 10^4 t in 1985 to 2.2 × 10^4 t in 2021, with the highest P output of 3.3 × 10^4 t in 2006 (Fig. 4(b)). The average annual outputs of N and P in Shaanxi Province in the past 35 years were 19.3 × 10^4 and 2.4 × 10^4 t, respectively. The outputs of N and P from animal husbandry were closely correlated with the quantities of livestock and poultry farmed. Among the animals, cattle contributed the most N and P due to higher N and P contents in their manure. Over the past 35 years, cattle breeding contributed an average 57.7% of N and 45.5% of P. In terms of loading on arable land, the highest N load was in Hanzhong city (106.6 kg·ha^{-1}), followed by Ankang city (93.7 kg·ha^{-1}) and Baoji city (72.5 kg·ha^{-1}) (Table 7), while the lowest N load was observed in Xi'an city at 25.5 kg·ha^{-1}. The average N load due to animal husbandry in Shaanxi Province in 2021 was 58.2 kg·ha^{-1}. Similarly, the highest P load was observed in Hanzhong city at 24.2 kg·ha^{-1}, followed by Ankang city (21.2 kg·ha^{-1}) and

Table 6 Arable land load of LM and the pollution risk index of LM in various cities of Shaanxi Province in 2021

Region	Cites	Cow (10^4 t)	Poultry (10^4 t)	Pig (10^4 t)	Sheep (10^4 t)	Arable land load (t·ha^{-1})	R-value
Guanzhong Area	Xi'an	57.6	19.7	46.7	10.8	5.2	0.2
	Tongchuan	14.6	8.7	11.4	4.9	5.9	0.2
	Baoji	318.8	21.1	102.3	82	17.4	0.6
	Xianyang	154.7	28.9	199.9	61.8	12.9	0.4
	Weinan	231.4	56.7	212.6	84.8	11.1	0.4
Northern Shaanxi	Yan'an	70.9	10.4	61.4	90.3	15.9	0.5
	Yulin	212.3	26.6	147.6	792.7	16.2	0.5
Southern Shaanxi	Hanzhong	285.3	29.6	243.6	41.6	23.8	0.8
	Ankang	211.6	25.6	185.7	83.5	22.8	0.8
	Shangluo	77.6	38	80.8	33.2	14.5	0.5

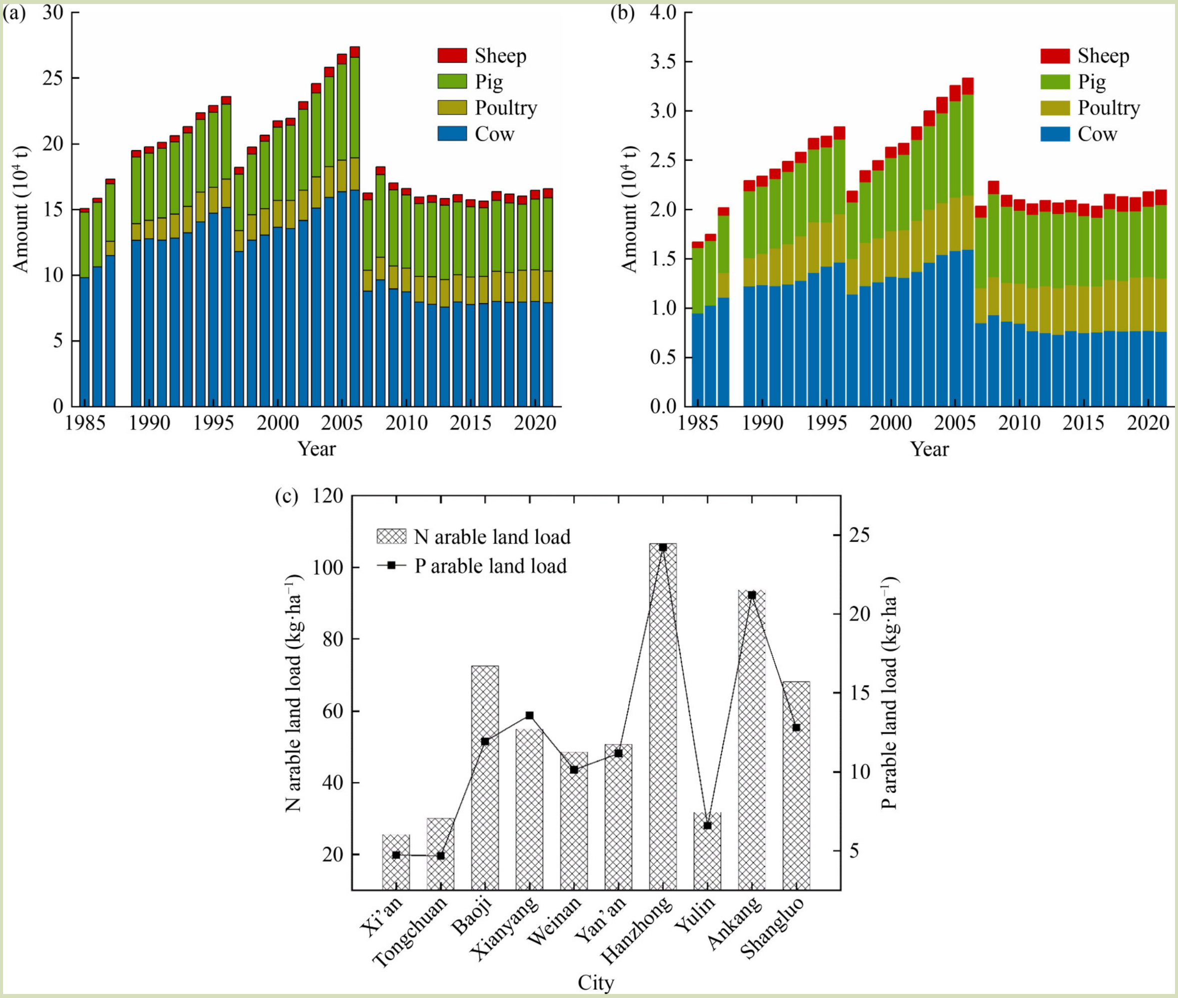


Fig. 4 Amounts of (a) N and (b) P of LM in Shaanxi Province from 1985 to 2021; (c) N and P loads of arable land.

Table 7 Spatial distribution of N and P loads of arable land for Shaanxi Province in 2021

Region	City	Arable land load of N (t·ha^{-1})	Arable land load of P (t·ha^{-1})
Guanzhong Area	Xi'an	25.5	4.7
	Tongchuan	30.1	4.7
	Baoji	72.5	11.9
	Xianyang	54.9	13.6
	Weinan	48.5	10.1
Northern Shaanxi	Yan'an	50.7	11.2
	Yulin	31.8	6.6
Southern Shaanxi	Hanzhong	106.8	24.2
	Ankang	93.7	21.2
	Shangluo	68.0	12.8

Xianyang city (13.6 kg·ha^{-1}) (Table 7), while the lowest P load occurred in Xi'an city and Tongchuan city at 4.7 kg·ha^{-1} each. The average P load in Shaanxi Province in 2021 was 12.1 kg·ha^{-1}.

The carrying capacities of land for N and P in Shaanxi Province in 2021 were calculated by incorporating the cultivated and pasture land areas. The manure from other livestock and poultry was converted into pig manure equivalents using the total N and P emissions per unit of pig. Based on these calculations, the environmental carrying capacity and the total scale of livestock and poultry farming were determined for each city in Shaanxi Province for year 2021. Due to the separation between animal husbandry and crop cultivation in China, as well as issues such as a shortage of labor directly engaged in agriculture and challenges in the long-distance transportation of LM, chemical fertilizers are widely applied on the farmland in most regions[43,44]. Therefore, the impact of fertilizer application must be considered when assessing the environmental capacities for N and P of arable land and pasture land. Assuming that all N and P originated from LM, and alternatively, assuming that 50% of N and P originated from LM, the environmental carrying capacity for livestock and poultry farming in each region was estimated and presented in Table 8. Based on the total N and P, the livestock and poultry farming scales in Shaanxi Province for 2021 were 26 million pig equivalents and 41 million pig equivalents, respectively. These quantities had not exceeded the environmental carrying capacities (40.4 million pig equivalents for N and 62.7 million pig equivalents for P) of animal husbandry in Shaanxi Province. However, the scales of livestock and poultry farming in Hanzhong and Ankang had exceeded their respective environmental carrying capacities, indicating higher risks of N and P pollutions. These regions are known for having relatively large livestock and poultry quantities in Shaanxi Province, and thus, attention should be given to environmental protection in these areas. Currently, scholars have pointed out that there is an increasing mismatch between animal husbandry scale and arable land carrying capacity, leading to severe pollution caused by LM[45].

3.4 Biogas potential of livestock and poultry manure in Shaanxi Province from 1985 to 2021

Figure 5 presents the theoretical biogas potentials of various types of LM in Shaanxi Province from 1985 to 2021. Among them, cattle manure contributed most to biogas production, with percentage ranging from 43.9% to 63.8%. Pig manure followed with a contribution ranging from 19.8% to 30.7%. Other types of LM exhibited relatively smaller biogas potentials, primarily due to the larger numbers of cattle and pigs than other livestock in the region. Over the past 35 years, the average annual biogas potential of LM in Shaanxi Province was 5.2×10^9 m^3.

Table 9 displayed the theoretical biogas potentials of LM in various regions of Shaanxi Province in 2021. The overall biogas potential for Shaanxi Province in 2021 was 4.7×10^9 m^3, with a regional average of 4.7×10^8 m^3. Regions with relatively higher biogas potentials included Yulin City at 1.1×10^8 m^3, Hanzhong City at 6.7×10^8 m^3, and Weinan City at 6.3×10^8 m^3, whereas regions with relatively lower biogas potentials included Tongchuan City at 4.3×10^7 m^3, Xi'an City at 1.5×10^8 m^3, and Yan'an City at 2.3×10^8 m^3.

Table 8 Animal husbandry environmental carrying capacity, actual quantity of livestock and poultry farmed, and LM pollution risk index in Shaanxi Province in 2021

City	Environmental capacity (10^4 t)		Environmental capacity of LM (10^4 pigs)		Actual environmental capacity calculated by pig manure (10^4 pigs)		Actual breeding quantity calculated by pig manure (10^4 pigs)		Pollution risk index	
	N	P	N	P	N	P	N	P	N	P
Xi'an	4.4	0.9	693.6	1073.7	346.8	536.9	104.2	145.2	0.2	0.1
Tongchuan	1.1	0.2	180.6	279.6	90.3	139.8	31.9	37.4	0.2	0.1
Baoji	5.1	1.1	809.5	1253.2	404.8	626.6	345.0	427.8	0.4	0.3
Xianyang	5.9	1.2	927.9	1436.3	463.9	718.2	299.9	558.3	0.3	0.4
Weinan	9.0	1.9	1425.8	2207.1	712.9	1103.6	407.0	640.0	0.3	0.3
Yan'an	2.5	0.5	394.7	611.0	197.4	305.5	117.8	195.0	0.3	0.3
Hanzhong	4.3	0.9	679.6	1052.0	339.8	526.0	426.0	727.8	0.6	0.7
Yulin	12.4	2.5	1960.0	3034.2	980.0	1517.1	366.4	572.1	0.2	0.2
Ankang	3.8	0.8	597.1	924.3	298.5	462.1	329.2	559.6	0.6	0.6
Shangluo	2.7	0.6	427.6	661.9	213.8	331.0	171.1	242.5	0.4	0.4

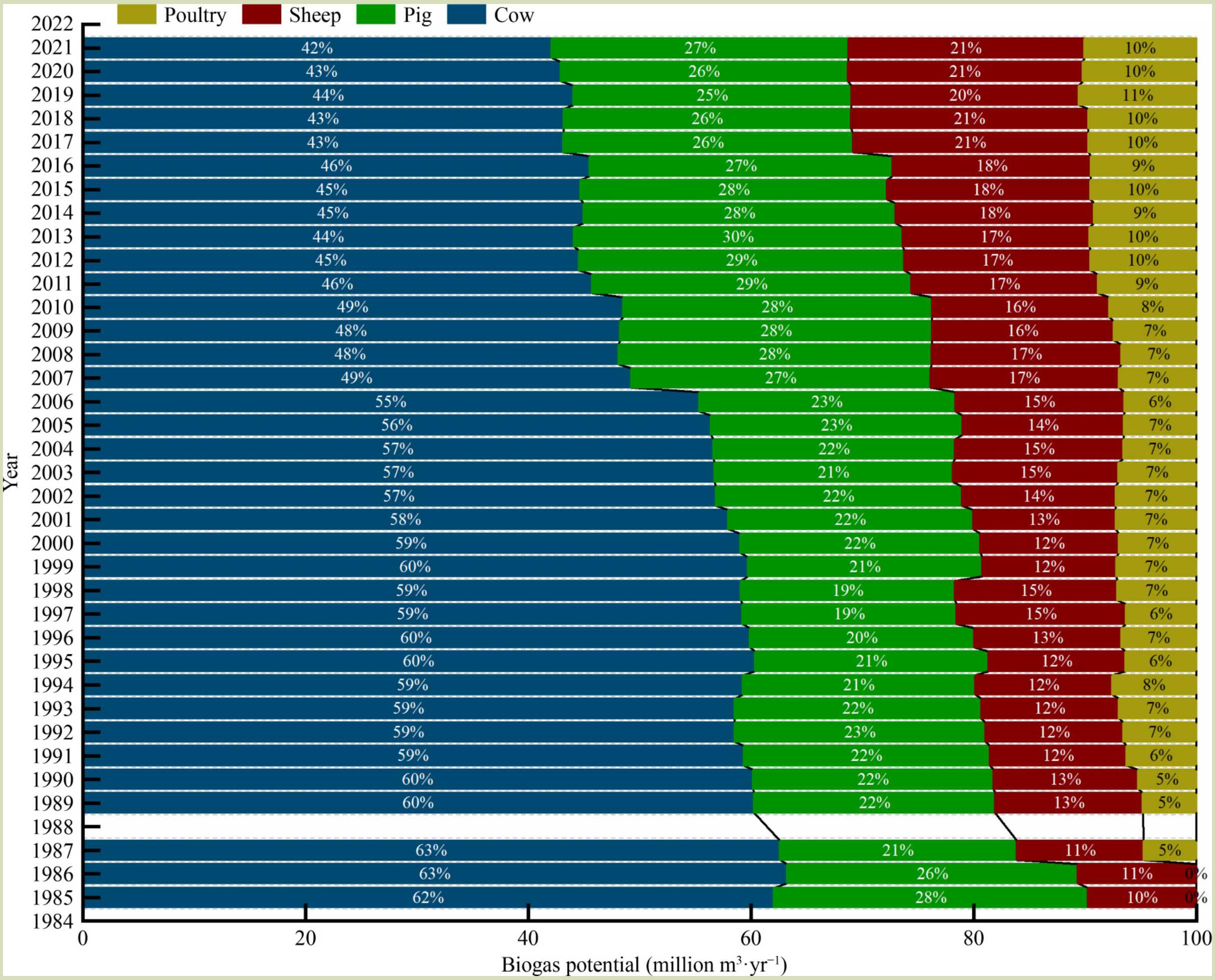


Fig. 5 Biogas potential of LM in Shaanxi Province from 1985 to 2021.

Table 9 Biogas potential of cities in Shaanxi Province according to statistical data for 2021

City	Biogas potential (million $m^3 \cdot yr^{-1}$)				
	Cow	Pig	Sheep	Poultry	Total
Xi'an	71.9	46.7	8.7	21.8	149.1
Tongchuan	18.3	11.4	4.0	9.6	43.3
Baoji	398.5	102.3	66.7	23.3	590.8
Xianyang	193.3	199.9	50.3	32.0	475.4
Weinan	289.3	212.6	68.9	62.6	633.4
Yan'an	88.6	61.4	73.4	11.4	234.8
Hanzhong	356.6	243.6	33.8	32.7	666.7
Yulin	265.3	147.6	644.5	29.4	1086.8
Ankang	264.5	185.7	67.8	28.3	546.3
Shangluo	97.0	80.8	27.0	42.0	246.8

Based on the data, the biogas energy potential of LM in Shaanxi Province in 2021 reached approximately 1.1×10^{11} MJ, which was equivalent to about 3.8×10^6 t standard coal, 2.6×10^6 t crude oil, or 2.8×10^9 m^3 natural gas. The total energy consumption in Shaanxi Province in 2021 was 1.4×10^8 t standard coal equivalent, with 73.69% of the energy contributed by coal, 6% by petroleum, 10.4% by natural gas and 9.91% by hydropower. Therefore, biogas from LM can meet approximately 2.7% of the annual energy demand, indicating that biogas can serve as a stable and reliable source of energy. The calculated values in this study are relatively high due to two main reasons: the large scale of livestock industry in Shaanxi Province and the omission of factors, such as the utilization methods of manure and losses during transportation, from the calculations.

3.5 Carbon emission reduction potential of LM in Shaanxi Province

Reducing carbon emissions is a pressing issue related to the survival of mankind, and achieving carbon neutrality has become the common goal of many countries, especially the developed ones. China has issued the Guiding Principles on Accelerating the Establishment and Improvement of a Green and Low-carbon Circular Economic System[46]. Together with the "Government Work Report 2023"[47], they emphasize energy conservation and carbon reduction, promote energy security and stable energy supply with green and low-carbon sources, and advance the attainment of peak carbon emissions and carbon neutrality scientifically. According to our calculations, the livestock and poultry in Shaanxi Province emitted 2.25 million tons of carbon in 2021 (Table 10). Carbon emissions from livestock and poultry should be minimized to achieve the targets of carbon emissions. This can be measured with indicators comprising carbon emission reduction potential and carbon emission reduction potential scale (relative to production). Based on the data in Table 10 and Table 11, it can be seen that the average carbon reduction potential of Shaanxi Province over the past 10 years was 22%, with the largest carbon emission reduction potential in 2018 at 45%. From 2012 to 2021, the average carbon emission reduction potential scale of Shaanxi Province was 10%, with largest carbon emission reduction potential scale in 2018 at 21.5%.

4 Discussion

4.1 The reasons for large-scale utilization of LM in Shaanxi Province

The sustainable development of the livestock industry and environmental protection are mutually beneficial. The foundation for this sustainable development is green and low-carbon practices. It is essential to promote the utilization of livestock waste, particularly LM, for better environmental protection.

Table 10 Total carbon emissions of animal husbandry in Shaanxi Province from 2012 to 2021

Year	Total carbon emissions (10^4 t·yr^{-1})	Year	Total carbon emissions (10^4 t·yr^{-1})
2012	198.50	2017	221.92
2013	196.06	2018	220.09
2014	204.41	2019	213.03
2015	201.05	2020	222.68
2016	197.83	2021	224.97

Table 11 Optimal total carbon emissions of animal husbandry in Shaanxi Province from 2012 to 2021

Year	Optimal total carbon emissions (10^4 t·yr^{-1})	Year	Optimal total carbon emissions (10^4 t·yr^{-1})
2012	123.08	2017	141.99
2013	131.01	2018	120.31
2014	130.53	2019	213.03
2015	131.16	2020	222.68
2016	197.83	2021	224.97

In summary, the production volume of LM is directly influenced by the scale and structure of animal husbandry, with factors such as market dynamics, policies, and risks also exerting significant influences. Year 2006 marked a significant change in the production volume of LM in Shaanxi between 1985 and 2021. Prior to 2006, the livestock industry was in a phase of unregulated expansion, which primarily focused on increasing production due to growing market demand. During this period, cattle constituted the largest proportion in the livestock structure, followed by pigs and sheep, with poultry having the smallest proportion. This led to an overall increase in the production volume of LM. However, around 2006, the scale of livestock farming reduced significantly due to the impact of avian influenza and Porcine Reproductive and Respiratory Syndrome. In response to these risks, regulatory authorities began emphasizing efficiency and technological improvement, and thus, advocating for the establishment of large-scale and regulated animal husbandry[48]. Consequently, starting from 2007, there has been a gradual shift in the livestock structure, with the most noticeable change being a sharp decrease in the proportion of cattle and a slight drop in the proportion of pigs. Despite a reduction in the production volume of LM, the total amount of LM remains substantial, and this presents a significant potential for LM utilization.

In various cities of Shaanxi, the R-values of LM generally range from 0.2 to 0.8, with an average of 0.49, which is relatively low. This is attributed to the relatively large arable land area in Shaanxi. However, it is crucial not to overlook specific regions, such as Ankang and Hanzhong. Additionally, cow and pig manure contribute significantly to the N and P loads on cultivated land. If LM is not effectively utilized, it presents a significant environmental risk in the future, particularly if there is a continuous increase in the quantity of LM generated due to changes in farming scale and structure. Therefore, pollution prevention and control in Shaanxi, while addressing this issue comprehensively, should focus particularly on the cities of Ankang and Hanzhong, and the cattle and pig farming industries.

4.2 The potential for utilization of LM in Shaanxi Province

If the LM in Shaanxi is utilized for biogas production, it has the potential to meet 2.7% of the province's annual energy demand. In 2021, the biogas generation potential was estimated to be 1.1×10^{11} MJ, equivalent to 3.8×10^{6} t standard coal. The areas with significant biogas generation potential from cow and pig manure include Yulin, Hanzhong, and Weinan. It is important to note that the estimation of biogas generation potential in this study might be slightly higher than actual data because it did not account for losses during the transportation of LM. Nevertheless, the utilization of LM for biogas generation in Shaanxi is deemed to be a stable and reliable source of biomass energy.

From 2016 to 2021, the actual carbon emissions were close to the optimal level, indicating that carbon emissions had not reached a critical point that would cause substantial environmental pollution. However, there is an overall increasing trend in carbon emissions. If measures are not taken to reduce carbon emissions through the utilization of LM, there is a risk of increased carbon emissions in the future. It is important to note that the calculation of carbon emissions in this study only considered factors such as land, livestock industry asset inputs, and personnel. Other factors were not accounted for, and this could introduce some margin of error to the results.

4.3 Policy recommendations

In the context of global climate governance, achieving the goals of peak carbon emissions and carbon neutrality in the livestock industry requires a proactive and steady approach, rather than a reactive one. A fundamental measure is to further promote the utilization of LM through policy initiatives.

Firstly, planning should be undertaken from the perspective of harmonious coexistence between humans and nature, considering resource availability and environmental carrying capacity. The estimations of N and P loads on cultivated land and carbon emissions from LM generated provide essential data for policy formulation.

Secondly, an integrated and coordinated governance approach is necessary. Pollution control and utilization of LM should involve collaboration among provincial agricultural, environmental, and technological departments, as well as coordination of different local governments within the province. Initiatives should begin in areas with higher pollution levels and specific types of livestock farming. A systematic approach should be adopted to address the root causes of the problem, with a focus on the long-term effects of environmental governance. At provincial level, optimizing and adjusting the farming structure, along with upgrading processes, technologies, and equipment, can effectively control greenhouse gas emissions, thus, facilitating the green and low-carbon transformation of the livestock industry.

Thirdly, a combination of legal, market, and social instruments is crucial. Implementing strict environmental regulations, assessment systems guided by green development principles, mechanisms to hold polluters responsible, as well as measures such as market policies and green financial systems can ensure that livestock producers adopt clean production while receiving reasonable returns through effective utilization of LM. Meanwhile, the promotion of ecological civilization and the concept of green, low-carbon living throughout the society can motivate the public to protect the environment.

5 Conclusions

This study explored the spatiotemporal distribution of LM, as well as calculated the N-P loads, biogas potential, and carbon emission reduction potential of LM in Shaanxi Province. The major findings are as below.

Firstly, from 1985 to 2021, LM in Shaanxi Province increased by 1.26 times, reaching 46.356 million tons in 2021. LM in Shaanxi Province was mainly concentrated in northern Shaanxi, as well as central, western, and eastern Hanzhong city. LM in Shaanxi Province mainly came from cattle and pigs.

Secondly, regarding the environmental risks of LM, in 2021, the average LM load of arable land in Shaanxi Province was 14.57 $t \cdot ha^{-1}$, significantly lower than the limit value of 30 $t \cdot ha^{-1}$. This indicates that the farmland in Shaanxi Province can still absorb a significant amount of LM, thus, highlighting the need to vigorously promote the utilization of LM. Although the overall scale of livestock and poultry farming in Shaanxi Province has not exceeded the environmental capacity, the livestock and poultry farming in certain regions such as Hanzhong and Ankang has already surpassed their respective environmental capacities, posing high risks of N and P pollutions. The LM in Shaanxi Province possesses immense potential for biogas production. Large-scale biogas projects are recommended to promote the efficient utilization of LM as a clean energy source to facilitate the achievement of peak carbon emissions and carbon neutrality targets. Carbon emissions from livestock and poultry in Shaanxi Province reached 224.97×10^4 t in 2021. By employing the SBM model, the average carbon emission reduction potential of animal husbandry in Shaanxi Province over the past decade was estimated to be 22%. The average carbon emission reduction scale in Shaanxi Province from 2012 to 2021 was 10%. Currently, the carbon emissions of Shaanxi Province are still at an ideal level. However, if the treatment and utilization of LM are not promoted, the increasing annual carbon emissions could increase the associated environmental risks.

Thirdly, it is noteworthy that the LM in Shaanxi Province possesses significant potential for energy generation, and this could offer substantial environmental benefits.

Fourthly, it is recommended to initiate large-scale biogas projects in areas producing significant quantities of LM, such as Hanzhong and Ankang. Biogas can serve as a clean alternative to some conventional energy sources.

Fifthly, from policy perspective, this study suggests that continuous assessment of environmental risks associated with LM should be undertaken. As such, the governance and utilization of LM should be coordinated through a systematic approach, which focuses on regions and types of livestock farming producing higher pollution levels. Additionally, efforts should be made to optimize the livestock industrial structure, foster technological innovation, implement tax incentives, address market dynamics, comply with legal requirements, and stimulate intrinsic societal motivations. These comprehensive measures will effectively control greenhouse gas emissions and facilitate the green and low-carbon transformation of the livestock industry.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (32172679 and 31902122).

Compliance with ethics guidelines

Mengyuan Qiao, Jianchun Zhu, Ronghua Li, Junting Pan, Ran Xiao, Hailong Wang, Kuok Ho Daniel Tang, and Zengqiang Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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