Agronomy Research **23**(S1), 208–219, 2025
https://doi.org/10.15159/AR.25.029

Analysis of the potential of livestock excreta for urea production through anaerobic digestion: challenges and opportunities in Latin America

S. Villegas[1,*], L. Rocha-Meneses[2], M. Luna-delRisco[1], C. Arrieta-González[1] and M. González-Palacio[1]

[1]University of Medellín, Faculty of engineering, Carrera 87 #30-65, postal code 050026, Medellín, Colombia
[2]Estonian University of Life Sciences, Institute of Forestry and Engineering, 56 Fr.R. Kreutzwald Str., EE 51006 Tartu, Estonia
[*]Correspondence: svillegas@udemedellin.edu.co
All authors contributed equally to this work

Received: February 15th, 2025; Accepted: April 22nd, 2025; Published: April 22nd, 2025

Abstract. Urea is one of the most demanded fertilizers worldwide and in Latin America. The high dependence on international markets to meet the region's urea demand, the high consumption of fossil energy for its production, and greenhouse gas emissions increase agricultural production costs and create the need to seek alternative processes for urea production to reduce these adverse effects. In this sense, this work explores the possibility of producing urea in Latin America from the ammonia and CO_2 generated in the anaerobic digestion process of livestock excreta under conditions that favor the production of both gases. The results indicate that it is possible to meet the demand for urea for agricultural use by utilizing 15% of its theoretical potential obtained from livestock excreta. This new alternative for obtaining urea brings economic benefits, reduces greenhouse gas emissions, and fosters social development. However, it faces legal, infrastructure, and technological barriers that may hinder the adoption of this technology in rural areas of Latin America.

Key words: anaerobic digestion, fertilizer, Latin America, livestock excreta, urea.

INTRODUCTION

Currently, the world's population stands at 8.2 billion people and is expected to grow by up to 17% by 2054 (United Nations Department of Economic and Social Affairs (Population Division), 2024). Particularly, the growth rate is higher in developing countries, increasing the demand for agricultural products, meat, and consequently a greater consumption of fertilizers and a large generation of agricultural and livestock waste (Mukhtar, 2023). This scenario raises the need for increased exploitation of minerals and high fossil energy consumption to produce fertilizers rich in nitrogen (N), phosphorus (P), and potassium (K), which are the macronutrients involved in cultivating plant species (Zhao et al., 2016).

Urea is the most used fertilizer as a source of N, accounting for about 65% of global application (Zhang et al., 2023), due to its high N content – around 46% – and the fact that its solid form facilitates transportation and reduces volatilization compared to liquid fertilizers (Wang et al., 2021). According to information reported by the Food and Agriculture Organization (FAO), between 2018 and 2022, Latin America (LA) increased its imports of urea, exceeding 11.5 million tons per year, as well as its consumption for agricultural use, which was over 3.4 million tons per year (FAO, 2025). Additionally, it is projected that by 2050, global demand will increase by between 50% and 75% (Lim et al., 2021). The high level of imports and low local production of urea in LA cause fluctuations in its local price due to its dependence on the international market, which at the end of 2021 and the beginning of 2022 - at the onset of the conflict between Russia and Ukraine - reached a historic maximum, exceeding USD 1,200 per metric ton (Bolaños-Silva, 2023). The volatility in the price of fertilizers like urea directly impacts the production costs of agricultural and livestock foods in LA, which could be mitigated by local production that meets part of its demand.

On the other hand, the increase in the use of urea as a fertilizer and the consumption of fossil fuels for its production are responsible for 5% of CO_2 emissions (Gao & Cabrera Serrenho, 2023). This environmental issue is accompanied by a greater generation of animal excreta, due to the growth of the livestock sector, requiring adequate management to avoid methane emissions into the atmosphere and the pollution of soil and water bodies (Samoraj et al., 2022). In this context, the mitigation of environmental problems caused by urea production through the conventional Haber-Bosch process has been addressed by technologies that reduce the use of fossil fuels, enable the capture of CO_2 as a raw material, and seek to increase process efficiency (Erfani et al., 2024).

In the research carried out by Palys & Daoutidis (2024), modifications to the conventional Haber-Bosch process are analyzed by producing hydrogen via water electrolysis and extracting nitrogen from the air using solar photovoltaic and wind energy for its subsequent transformation into ammonia. Additionally, the use of biogenic CO_2 as a reagent to produce urea is proposed, employing ammonia obtained from renewable energies. The researchers conclude that these modifications reduce greenhouse gas emissions by not using natural gas to obtain hydrogen and by incorporating renewable energies to meet part of the energy demand required in the process. Furthermore, the use of biogenic CO_2, derived from bioethanol production, contributes to reducing the use of fossil carbon that is utilized in the conventional process. Similar conclusions were reached in the study by Wang et al. (2021). These researchers expand mitigation strategies, showing that the inclusion of bioenergy as another source of renewable energy and the recovery of heat during urea production significantly reduce emissions of polluting gases if these actions are also aligned with an efficient use of urea through correct planning and the implementation of appropriate practices in agricultural processes, as proposed by Zhang et al. (2023).

Instead, pollution mitigation associated with livestock waste has mainly been tackled through conventional technologies such as composting for recovering nutrients in the solid phase, and anaerobic digestion (AD) technology for the controlled production of biomethane and nutrient recovery in the liquid and solid fractions of the digestate (Dalke et al., 2021). Specifically, the use of AD has taken on greater relevance due to the importance of biomethane as renewable energy. Many studies have focused on optimizing the process to increase production, with one of the main challenges being to avoid ammonia (NH_3) inhibition of methanogenic microorganisms, which are responsible for methane production in AD (Jiang et al., 2019; Yang et al., 2024). However, the production of NH_3 and CO_2 during the AD of livestock excreta can be beneficial, as both substances are a biogenic source for urea production and, additionally, the energy consumption of AD for NH_3 production is lower than that required in the Haber-Bosch process.

Based on the above, a gap in the current state of knowledge is identified. Although several studies have explored the operational conditions of anaerobic digestion (AD) that favor the production of ammonia (NH_3) and carbon dioxide (CO_2), there is still no quantitative assessment of the theoretical potential for urea production from livestock excreta in Latin America, nor an analysis of how such production could help meet the fertilizer demand in the region.

In this sense, the scientific purpose of this study is to estimate the potential for urea production from livestock excreta in Latin America using anaerobic digestion technology under conditions that favor the generation of NH_3 and CO_2. Additionally, the practical purpose is to evaluate whether this process could represent a viable alternative to conventional urea production, considering that this new approach may reduce agricultural input costs, decrease greenhouse gas emissions, and promote the development of a rural industry based on the bioeconomy, while also acknowledging the existing challenges related to infrastructure, legal frameworks, and social aspects in Latin America.

MATERIALS AND METHODS

Urea trade, livestock and manure production data

The information on urea trade and the livestock sector in LA was obtained for the last 5 years reported in the FAO, (2025). Specifically, the analysis includes 34 Latin American countries for which consistent and comparable data were available, including: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay, and other Caribbean countries. Latin America, as defined in this study, covers an estimated area of approximately 20.1 million square kilometers, representing about 13% of the world's land surface (Latin America & Caribbean Surface Area 1961–2025 | MacroTrends, 2025). The region encompasses a wide variety of climate zones, including tropical, subtropical, arid, temperate, and highland climates. This climatic diversity influences both livestock production systems and fertilizer demand across the region (FAO, 2012). The selected components of the urea market were the imports, exports, production, and use in agriculture for each country in the region between 2018 and 2022. Similarly, for the livestock sector, data were extracted regarding the inventory of bovine, swine, and poultry animals between 2019 and 2023. From this information, the total annual amount was calculated by year and by type of livestock for each of the components of the urea trade and for the animal inventory in LA. The totalized results allowed for an analysis of the behavior and projection over time of the urea trade and the animal inventory.

Based on the studies and characterizations of livestock excreta reported by American Society of Agricultural Engineers (ASAE) (2005), for each livestock species, the average excreta production rate per animal (kg animal^{-1} day^{-1}) and the average nitrogen concentration in the excreta per amount excreta (g kg^{-1}) were obtained. This information was subsequently used to estimate the amount of nitrogen available annually for each type of excreta.

Anaerobic digestion conditions for ammonia production

The AD conditions that favor NH_3 production are determined under the assumption that they are close to generating inhibitory effects caused by nitrogenous species (NH_3 and NH_4^+) present in the process. To identify these operating conditions, an analysis was conducted of current research focused on determining the characteristics and parameters that influence AD inhibition and toxicity by nitrogenous species. For this purpose, the following search equation was constructed and used in the Elsevier (2025): (‘anaerobic digestion’ OR ‘biogas production’) AND (‘ammonia production’ OR ‘NH3 production’) AND (‘cattle manure’ OR ‘bovine manure’ OR ‘pig manure’ OR ‘poultry manure’ OR ‘chicken manure’) AND (‘optimization’ OR ‘operating conditions’ OR ‘efficiency’) AND (‘pH’ OR ‘temperature’ OR ‘organic loading rate’ OR ‘hydraulic retention time’).

The results produced by the search equation were filtered between 2018 and 2024 for research articles and review articles. From the filtered documents, an analysis was performed of articles focused on the efficiency of pilot-scale or industrial-scale AD of bovine, swine, and poultry excreta under pH, temperature, organic loading rate (OLR), and hydraulic retention time (HRT) conditions that favor NH_3 and NH_4^+ production.

Urea potential modeling

The previously obtained and analyzed information is used to estimate the potential for urea production and the percentage of its demand that can be met in LA. This estimation was carried out through six calculation steps described below.

Step 1: Calculation of the average annual population for each livestock species. Based on data provided by FAO (2025), the average annual population (number of animals) per species is estimated using the initial and final livestock inventory for each year:

$$AP_{i,j} = \frac{S_{i-1,j} + S_{i,j}}{2} \tag{1}$$

where i indicates the year from 2018 to 2023, j indicates the livestock species (bovine, swine, or poultry), $AP_{i,j}$ in (animal year^{-1}), is the average population, and $S_{i,j}$ in (animal year^{-1}) is the animal inventory for year i of species j, while $S_{i-1,j}$ in (animal year^{-1}) is the animal inventory from the previous year for species j.

Step 2: Calculation of the annual production of livestock excreta. The annual production of excreta for each type of livestock species is calculated from its average annual population and the average daily mass factor of excreta produced per animal using the following expression:

$$AMP_{i,j} = AP_{i,j} \times MD_j \times 365 \tag{2}$$

where $AMP_{i,j}$ in (kg year^{-1}) is the excreta production in year i of species j and MD_j in (kg animal^{-1} day^{-1}) is the daily excreta production factor per animal for species j.

Step 3: Calculation of organic nitrogen. The amount of organic nitrogen is estimated from the average concentration of inorganic and total nitrogen contained in each type of excreta reported by American Society of Agricultural Engineers (ASAE) (2005), as follows:

$$ON_{i,j} = AMP_{i,j}\left(CN_{T,j} - CN_{I,j}\right) \quad (3)$$

where $ON_{i,j}$ in (g year^{-1}) is the annual amount of nitrogen contained in the excreta of species j, while $CN_{T,j}$ in (g kg^{-1}) and $CN_{I,j}$ in (g kg^{-1}) are the total and inorganic nitrogen concentrations in the excreta of species j, respectively.

Step 4: Calculation of ammonia production. A percentage of the total amount of ammonia that can be produced from AD comes from the biological conversion of organic nitrogen, while the remaining percentage is obtained through the complete transformation of inorganic nitrogen into this substance. To calculate the total amount of ammonia, the contribution from organic nitrogen and from inorganic nitrogen is estimated using the following expressions:

$$NH_3^{AD}{}_{i,j} = ON_{i,j} \times R_{AD,j} \quad (4)$$

$$NH_3^{I}{}_{i,j} = AMP_{i,j} \times CN_{I,j} \quad (5)$$

$$NH_3^{T}{}_{i} = \sum\nolimits_j NH_3^{AD}{}_{i,j} + NH_3^{I}{}_{i,j} \quad (6)$$

where $NH_3^{AD}{}_{i,j}$ in (g year^{-1}) y $NH_3^{I}{}_{i,j}$ in (g year^{-1}) is the production in year i from the excreta of spicie j coming from organic and inorganic nitrogen, respectively. $R_{AD,j}$ in (g g^{-1}) is the yield of organic nitrogen conversion to ammonia through AD of the excreta of species j and $NH_3^{T}{}_{i}$ in (g year^{-1}) is the total amount of ammonia produced in year i.

Step 5: Urea production from ammonia. The production of urea ($CO(NH_2)_2$) from gaseous ammonia and carbon dioxide is limited by the stoichiometry and yield of the following reaction (Erfani et al., 2024):

$$2NH_3 + CO_2 = CO(NH_2)_2 + H_2O \quad (7)$$

Therefore, the expression that allows the estimation of urea production is the following:

$$UP_i = NH_3^{T}{}_{i} \times 1.765 \times R_U \quad (8)$$

where UP_i in (g year^{-1}) is the annual amount of urea produced, and R_U in (mol mol^{-1}) is the reaction yield for its production.

Step 6: Percentage of satisfaction of the urea demand. The analysis of data on the urea market in LA made it possible to calculate the total amount of urea used annually for agricultural purposes in the region. Therefore, the expression used to estimate the percentage of urea demand that can be covered by the urea produced from the AD of livestock excreta is the following:

$$PDS_U = \frac{UD_i}{UP_i} \times 100 \quad (9)$$

where PDS_U is the percentage of satisfied urea demand, while UD_i in (g year^{-1}) is the annual amount of urea used in agriculture for LA.

RESULTS AND DISCUSSION

Urea in Latin America

The urea market in LA was studied based on four factors reported in the FAO (2025): exports, imports, production, and agricultural use. Fig. 1 shows the behavior of the first 3 factors in the last 5 reported years, while Fig. 2 shows the amount of urea used in agriculture. Based on the information in Fig. 1, annual urea production has decreased each year, from 3.8 million tons in 2018 to 2.8 million tons in 2022, while imports increased in 2020 and 2021 to over 14 million tons, but then decreased again in 2022 to the levels exhibited in 2018 and 2019, not exceeding 12 million tons. The observed increase in urea imports during 2020 and 2021 may have been caused by the increase in local food production during the COVID-19 health crisis. This analysis is corroborated by the increase in the tons of urea used for agriculture reported for 2021 (Fig. 2).

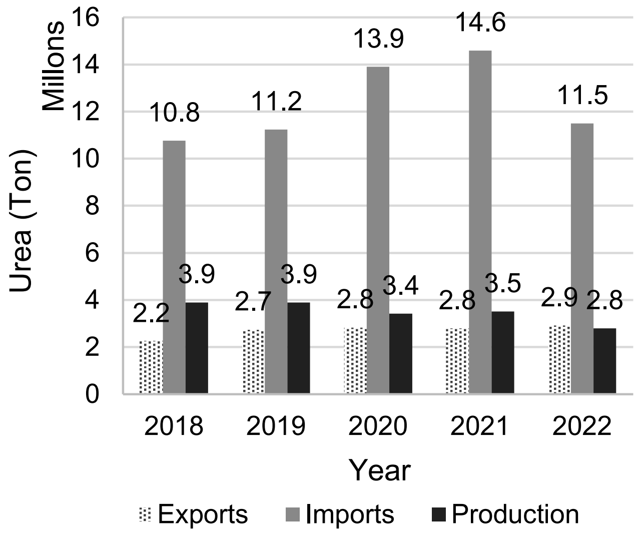

Figure 1. Urea Latin America trade.

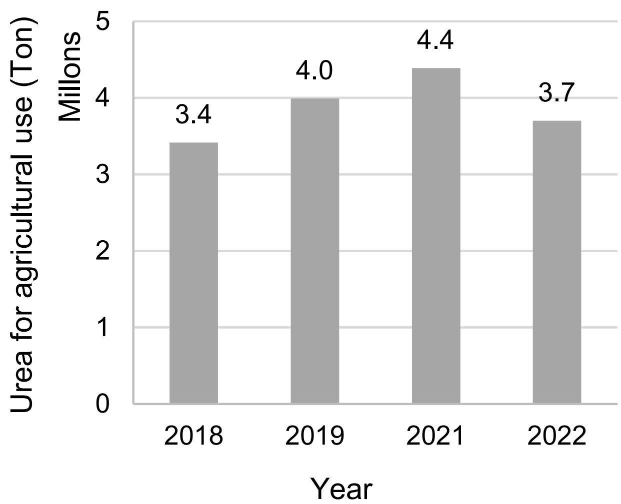

Figure 2. Urea for agricultural use in LA.

Regarding the levels of urea exported by LA, they have remained constant at around 2.8 million tons, indicating that LA has a stable market for urea sales. Moreover, it can be observed that urea import levels are higher than the levels of urea used in agriculture, representing at most 35% of the imported tons. This indicates the existence of other markets for urea in LA that can be supplied by local production, thus reducing costs in those markets.

Livestock in Latin America

Livestock production for bovine, swine, and poultry species is shown in Figs. 3–5, respectively. Each species exhibits sustained growth in animal population, with the poultry sector having the largest population – 3,936 million animals in 2023 – while the smallest population is in the swine sector, with 103 million animals in that same year.

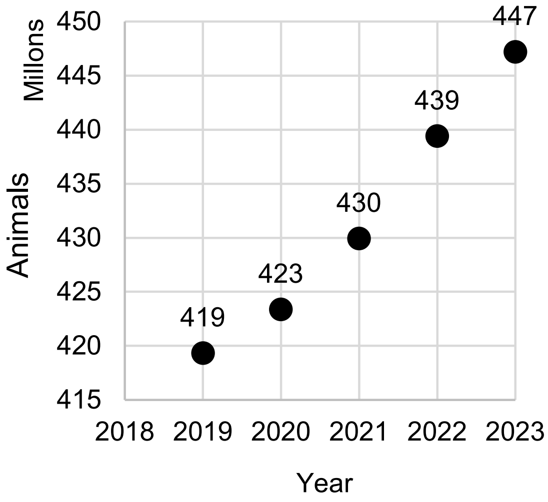

Figure 3. Cattle average population.

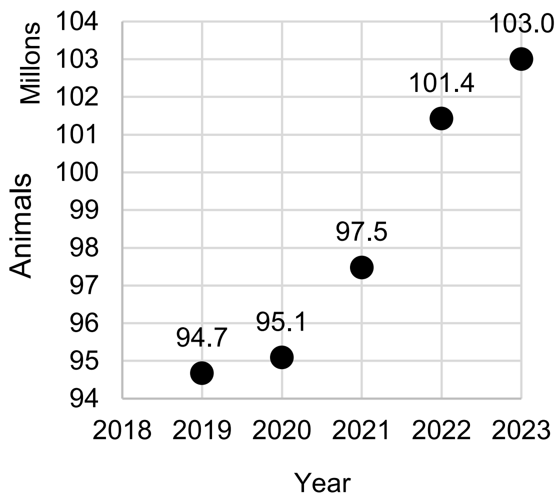

Figure 4. Pig average population.

The bovine sector shows a total increase of 6.6% between 2019 and 2023 and an average annual increase of 1.6%. Similarly, the total and average annual increase percentages for the swine sector are 8.8% and 2.1%, and for poultry 8.3% and 2.0%, respectively. These results and the highly linear trend exhibited by annual growth in animal populations for each species allow for low-uncertainty projections regarding future average populations, and thus in estimates concerning the volume of excreta and its nitrogen content.

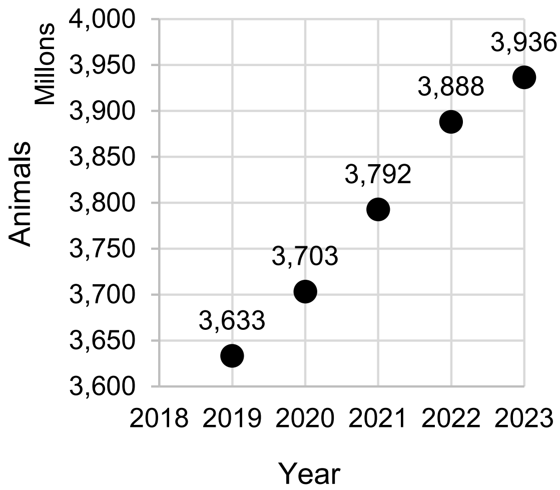

Figure 5. Chicken average population.

Furthermore, it is important to note that the swine and poultry sectors have intensive production systems, and therefore, collecting their excreta is technically less complex. These two sectors show the highest growth rates, whereas the bovine sector displays the lowest growth rate; in addition, there is greater difficulty in collecting bovine excreta due to the extensive nature of bovine production in much of LA.

Available nitrogen from livestock manure in LA

Table 1 shows the values of excreta production and the inorganic and total nitrogen content for each species reported in American Society of Agricultural Engineers (ASAE) (2005). Using these values and Equations 2 and 3, the amount of total and organic nitrogen contained in the excreta of each species is estimated.

Fig. 6 compares the total nitrogen content in the excreta of each species, showing that bovine excreta contain the highest amount of nitrogen due to the large amount of excreta produced per animal. Additionally, Table 3 presents the regression coefficients (R^2), which indicate the linear trend followed by the data series shown in Fig. 6. The slope values show that the total nitrogen content increases on average by 340,613, 23,504, and 46,185 tons per year for cattle, pig, and chicken manure, respectively. However, the poultry sector has the highest nitrogen concentration, and the swine sector the lowest. These characteristics of the excreta indicate that co-digestion of swine excreta with one of the other two types can shift the carbon/nitrogen ratio (C/N) toward nitrogen and, therefore, make it possible to increase NH_3 production through AD.

Table 1. Manure characteristics

Species	Production (kg animal^{-1} day^{-1})	Total Nitrogen (g kg^{-1})[2]	Inorganic Nitrogen (g kg^{-1})[2]
Cattle[1]	22.0	5.9	1.8
Pig[1]	3.8	5.3	3.0
Chicken[1]	0.088	18.2	10.0

[1]Data extracted from American Society of Agricultural Engineers (ASAE) (2005);

[2]Nitrogen concentration per kg of manure.

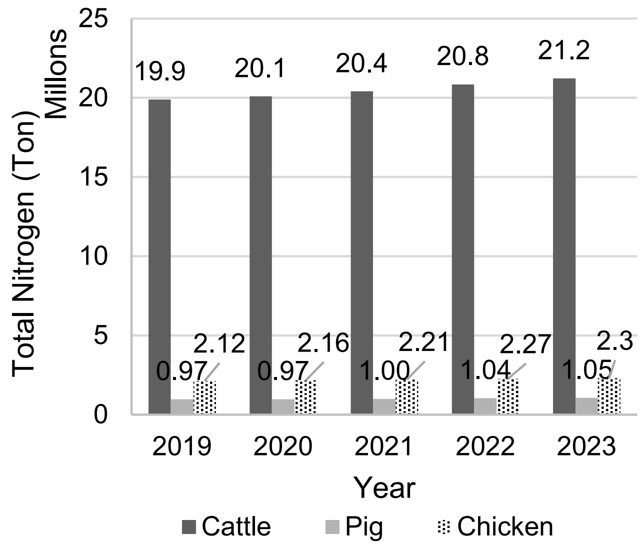

Figure 6. Urea for agricultural use in LA.

Anaerobic digestion conditions to produce ammonia

Ammonia production from anaerobic digestion requires a C/N below 20 and an alkaline pH in the reactor so that methanogenic bacteria are inhibited - preventing methane production – and allowing the transformation of ammonium ions into ammonia. However, a high pH also inhibits acidogenic bacteria, which are responsible for the deamination of amino acids and favor the formation of ammonium ions (Astals et al., 2018; Jiang et al., 2019; Yang et al., 2024). In this sense, the strategy proposed to increase the production and accumulation of ammonium ions, preventing the inhibition of acidogenic bacteria and allowing their subsequent conversion into gaseous NH_3, is to carry out AD in two stages.

The first stage is carried out under conditions that favor hydrolysis and acidogenesis, aiming to maximize the breakdown of complex organic compounds into amino acids and volatile fatty acids, thereby releasing and accumulating organic nitrogen in the form of ammonium ions (NH_4^+). Meanwhile, the second stage is carried out under conditions that shift the chemical equilibrium of the ammonium ion toward gaseous NH_3 and inhibit methanogenic microorganisms. Table 2 shows the operating conditions for each of the proposed stages. Additionally, in both proposed AD stages, there is continuous CO_2 production due to the decomposition of carbon-containing molecules; hence, the products with the highest concentration in the gas phase are NH_3 and CO_2.

Table 2. Anaerobic digestion conditions

Step	Process	C/N	pH	Temperature (°C)	Hydraulic retention time (day)	Product of interest
1	Hydrolysis and Acidogenesis	10–20	5.5–6.5	35–37	2–5	NH_4^+
2	Advanced Deamination		8.0–9.0	50–60	10–20	NH_3
Global conversion of AD[1]		Cattle manure: 60% – 75%; pig manure: 70% – 85%; chicken manure: 80% – 90%				

[1]The ranges are approximate for each type of manure and are obtained from the analysis of various research (Astals et al., 2018; Jiang et al., 2019; Samoraj et al., 2022; Yang et al., 2024).

Urea production and satisfaction of demand in Latin America

Fig. 7 shows the estimated ammonia production from the anaerobic digestion of excreta for each species. Ammonia production exhibits a linear growth trend for the whole species. Table 3 presents the regression coefficients (R^2), which confirm the linear trend followed by the data series shown in Fig. 7. The slope values show that the ammonia production increases on average by 244,717, 19,324, and 42,028 tons per year for cattle, pig, and chicken manure, respectively. From this behavior, the total ammonia production expected for 2025 is approximately 18.9 million tons, and considering a 95% yield for the urea production reaction (Eq. 7) (Palys & Daoutidis, 2024), about 31.5 million tons of this fertilizer could be obtained for the same year.

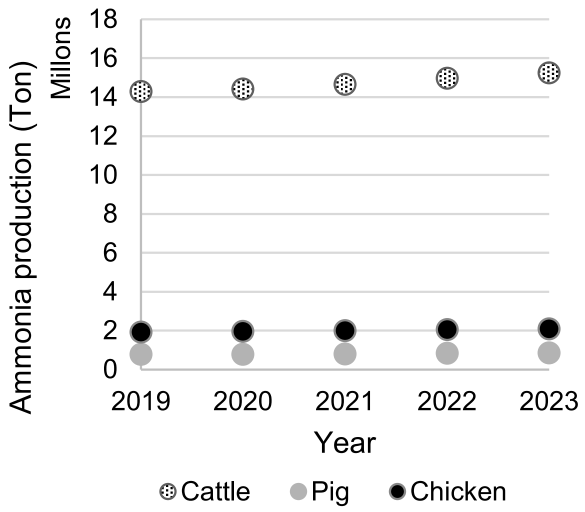

Figure 7. Ammonia production estimated in LA.

Finally, with this result, it can be observed that by utilizing 15% of the estimated potential for urea production, it would be possible to meet the demand for urea for agricultural use in LA, which still does not exceed 4.5 million tons per year (see Fig. 2). Regarding the annual urea imports, which have ranged between 10.8 and 14.6 million tons, they could be met if 47% of the estimated potential from the AD of livestock excreta were utilized.

Table 3. Lineal regression parameters

Figure	Variables	Species	Slope (ton year^{-1})	Y-intercept (ton)	R^2
Fig. 6	Total Nitrogen (predicted variable)	Cattle	340,613	2×10^7	0.98
	year (independent variable)	Pig	23,504	9×10^5	0.94
		Chicken	46,185	2×10^6	0.99
Fig. 7	Ammonia production	Cattle	244,717	-5×10^8	0.98
	(predicted variable)	Pig	19,324	-4×10^7	0.94
	year (independent variable)	Chicken	42,028	-8×10^7	0.99

Advantages and barriers to urea production in LA

The implementation of AD technology focused on ammonia production for its subsequent conversion into urea in LA offers significant advantages, but at the same time, faces different barriers that must be overcome.

Among the advantages are economic benefits, reduced environmental impacts, and social development. Economic benefits are achieved because local urea production from livestock excreta can reduce dependence on international production and prices, stabilizing local prices and lowering production costs in the agricultural sector. Moreover, this would improve food security and strengthen the region's economy. With respect to reducing environmental impacts, producing NH_3 and CO_2 via AD significantly decreases greenhouse gas emissions compared to the conventional Haber-Bosch process, which requires temperatures above 400 °C and pressures exceeding 150 bar, while AD can operate at a maximum temperature of 50 °C and at atmospheric pressure. Additionally, the proper management and utilization of excreta would greatly reduce soil and water pollution. Further advantages related to social development stem from job creation in rural areas by adopting new technologies such as the one proposed here, technological investment in the agricultural sector, and improvements in education focused on teaching more appropriate management and utilization of livestock waste.

On the other hand, the barriers to be overcome are associated with the technological and infrastructural limitations present in LA for medium- and large-scale AD implementation, as well as the high initial investment required. Moreover, in many LA countries there are no regulatory frameworks or clear policies to encourage the use of new technologies for urea production. Finally, another major barrier is the unfavorable perception that farmers may have regarding these technologies; thus, government programs and demonstration projects showcasing the benefits of their implementation would be key strategies for achieving acceptance in the rural sector.

CONCLUSIONS

Anaerobic digestion focused on NH_3 production also produces CO_2, making it possible to obtain the reactants for urea production in a single process with low pressure and low energy consumption. The demand for urea for agricultural use can be met by utilizing 15% of the estimated potential, which reduces dependence on imports and problems associated with fertilizer price volatility in the international market. All the environmental benefits arising from adopting this technology – such as proper excreta management, reduced greenhouse gas emissions, and waste utilization – help guide the agricultural sector toward a circular economy. The feasibility of implementing this technology requires closing gaps with governmental support through the creation of specific policies aimed at improving infrastructure, providing financing, developing training programs, and enhancing the quality of life of the rural population.

Future research should focus on estimating the actual technical potential for urea production from anaerobic digestion, considering the technological and infrastructural limitations in Latin America, as well as on long-term evaluations of process sustainability.

ACKNOWLEDGEMENTS. This work was made possible thanks to the support of the Science and technology Vice Rectory and the Faculty of Engineering of the University of Medellin.

REFERENCES

American Society of Agricultural Engineers (ASAE). 2005. Manure Production and Characteristics. In *ASAE Standards*, 1–19. American Society of Agricultural and Biological Engineers.

Astals, S., Peces, M., Batstone, D.J., Jensen, P.D. & Tait, S. 2018. Characterising and modelling free ammonia and ammonium inhibition in anaerobic systems. *Water Research* **143**, 127–135. https://doi.org/10.1016/j.watres.2018.06.021

Bolaños-Silva, L.G. 2023. Incidents in Corporate Social Responsibility as a consequence of the supply of fertilizers of Russian origin in Latin American markets. *Revista científica anfibios* **6**(2), 23–30. https://doi.org/10.37979/afb.2023v6n2.133 (in Spanish).

Dalke, R., Demro, D., Khalid, Y., Wu, H. & Urgun-Demirtas, M. 2021. Current status of anaerobic digestion of food waste in the United States. *Renewable and Sustainable Energy Reviews* **151**, 111554. https://doi.org/10.1016/j.rser.2021.111554

Elsevier. (2025). *Scopus - Document search*. https://scopus.unalproxy.elogim.com/search/form.uri?display=basic&zone=header&origin=#babas Accessed 21.01.2025

Erfani, N., Baharudin, L. & Watson, M. 2024. Recent advances and intensifications in Haber-Bosch ammonia synthesis process. *Chemical Engineering and Processing - Process Intensification* **204**, 109962. https://doi.org/10.1016/j.cep.2024.109962

FAO (Food and Agriculture Organizarion of the United Nation). 2012. *Global ecological zones for FAO forest reporting: 2010 Update*.**179.** Rome, pp. 52

FAO (Food and Agriculture Organizarion of the United Nation). 2025. *FAOSTAT.* https://www.fao.org/faostat/en/#data/QCL Accessed 21.01.2025

Gao, Y. & Cabrera Serrenho, A. 2023. Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nature Food* **4**(2), 170–178. https://doi.org/10.1038/s43016-023-00698-w

Jiang, Y., McAdam, E., Zhang, Y., Heaven, S., Banks, C. & Longhurst, P. 2019. Ammonia inhibition and toxicity in anaerobic digestion: A critical review. In *Journal of Water Process Engineering* **32**, 100899. https://doi.org/10.1016/j.jwpe.2019.100899

Latin America & Caribbean Surface Area 1961–2025 | MacroTrends 2025. https://macrotrends.net/global-metrics/countries/LCN/latin-america-caribbean-/surface-area-km?utm Accessed 19.04.2025

Lim, J., Fernández, C.A., Lee, S.W. & Hatzell, M.C. 2021. Ammonia and Nitric Acid Demands for Fertilizer Use in 2050. *ACS Energy Letters* **6**(10), 3676–3685. https://doi.org/10.1021/acsenergylett.1c01614

Mukhtar, Z. 2023. The Impact of the Ukraine-Russia War on Food Security and Countries Exposed to Food Supply Shock. *European Journal of Business and Management Research* **8**(2), 38–43. https://doi.org/10.24018/ejbmr.2023.8.2.1861

Palys, M.J. & Daoutidis, P. 2024. Techno-economic optimization of renewable urea production for sustainable agriculture and CO2 utilization. *Journal of Physics: Energy* **6**(1), 015013. https://doi.org/10.1088/2515-7655/ad0ee6

Samoraj, M., Mironiuk, M., Izydorczyk, G., Witek-Krowiak, A., Szopa, D., Moustakas, K. & Chojnacka, K. 2022. The challenges and perspectives for anaerobic digestion of animal waste and fertilizer application of the digestate. *Chemosphere* **295**, 133799. https://doi.org/10.1016/j.chemosphere.2022.133799

United Nations Department of Economic and Social Affairs (Population Division). 2024. *World Population Prospects 2024: Summary of Results*. https://desapublications.un.org/publications/world-population-prospects-2024-summary-results Accessed 25.01.2025

Wang, H., Palys, M., Daoutidis, P. & Zhang, Q. 2021. Optimal Design of Sustainable Ammonia-Based Food–Energy–Water Systems with Nitrogen Management. *ACS Sustainable Chemistry & Engineering* **9**(7), 2816–2834. doi: 10.1021/acssuschemeng.0c08643

Yang, J., Zhang, J., Du, X., Gao, T., Cheng, Z., Fu, W. & Wang, S. 2024. Ammonia inhibition in anaerobic digestion of organic waste: a review. *International Journal of Environmental Science and Technology*, 1–16. https://doi.org/10.1007/s13762-024-06029-1

Zhang, Y., Wang, W. & Yao, H. 2023. Urea-based nitrogen fertilization in agriculture: a key source of N2O emissions and recent development in mitigating strategies. *Archives of Agronomy and Soil Science* **69**(5), 663–678. doi: 10.1080/03650340.2022.2025588

Zhao, J., Ni, T., Li, J., Lu, Q., Fang, Z., Huang, Q., Zhang, R., Li, R., Shen, B. & Shen, Q. 2016. Effects of organic–inorganic compound fertilizer with reduced chemical fertilizer application on crop yields, soil biological activity and bacterial community structure in a rice–wheat cropping system. *Applied Soil Ecology* **99**, 1–12. doi: 10.1016/j.apsoil.2015.11.006