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Article

Connectivity and centralization in the movement of pigs in the state of Mexico (2017-2021): an approach to alignment with the Sustainable Development Goals (SDG)

Gabriela Berenice Vilchis Granados [a]

Nicolás Callejas Juárez [b]

Julieta Gertrudis Estrada Flores [a]

María Elena Trujillo Ortega [c]

Francisco Ernesto Martínez Castañeda [a*]

[a] Universidad Autónoma del Estado de México. Instituto de Ciencias Agropecuarias y Rurales. 50200, Toluca, Estado de México, México.

[b] Universidad Autónoma de Chihuahua. Facultad de Zootecnia y Ecología. Chihuahua, México.

[c] Universidad Nacional Autónoma de México. Facultad de Medicina Veterinaria y Zootecnia. Ciudad de México, México.

*Corresponding author: femartinezc@uaemex.mx

Abstract:

The structure of the pig movement network in the State of Mexico was analyzed. Through the analysis of social networks, the main municipalities of origin and destination that participated in the commercialization of pigs for the slaughter, fattening, breeding, and livestock fair markets were identified, evaluating their centrality and betweenness in the network. The data from pig movement records authorized by the National Service for Agrifood Health, Safety, and Quality (SENASICA, for its acronym in Spanish) correspond to the period from 2017 to 2021. The results indicated that the general structure of the network is highly centralized in a small number of municipalities, such as La Paz and Ecatepec de Morelos, which functioned as key nodes in the distribution of pigs. This centralization favored commercial efficiency by guaranteeing a constant flow to strategic markets, contributing to food security and economic growth in the most connected municipalities. Nonetheless, important risks were also identified, such as vulnerability to network interruptions, economic inequalities between municipalities, and the generation of bottlenecks in distribution. In addition, the low density of connections between municipalities could limit network cohesion, highlighting the need to diversify trade relationships and strengthen connectivity to reduce risks and promote a more equitable and resilient network.

Keywords: Information flow, Public policy, Food security, Transport.

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Introduction

In 2022, global meat production reached 122’585,397 t, with China as the leader[1], generating 46 % of global pork production, equivalent to the combined production of the 16 major producing countries. By 2033, global production is projected to increase from 122 million t in 2033 to 131 million, as is global pork consumption in all regions except Europe[2].

Population growth and increased purchasing power have driven intensive pig production that is increasingly dependent on technology and less linked to land, which has reoriented the debate towards the environmental impacts of population growth and its effect on the availability of natural resources[3,4]. In Mexico, in 2022 the country ranked as the 11th largest producer internationally and as the second largest importer of pork[1]. Pork protein was the most imported by the country[5], mainly from the United States and Canada, whose intensive pig production systems have grown significantly, favoring large farms that contribute to the global demand for meat[6].

In 2023, 16’555,726 breeding sows were in the main mega pig farms[7], although the rest come from small and medium-sized farms. In Mexico, there are 2,632 farms according to their zootechnical function[8]. Small-scale or backyard production units generate between 20 and 30 % of pork and represent 40 % of the animal inventory, with approximately 20,000 producers in rural municipalities[8]. Despite the importance of small producers, government subsidies are limited, generating unequal competition[9]. There is a positive relationship between access to credit and increased production of stable-growing species such as pigs[10].

In municipalities, pig production is essential for food security and economic well-being, representing up to 50 % of family income in some rural areas[11,12], they serve as suppliers of inputs in other activities[13] and are the basis of the country's political and administrative organization[14]. The State of Mexico, with 125 municipalities and 16'992,418 inhabitants, has a deficit in pork production, with a total volume of 22,408 t[15,16].

Social network theory is a valuable tool for analyzing market structure as it describes the connections between actors and value chains through measures of centralization and clustering[17]. These tools make it possible to address problems and propose solutions for pig production and distribution. Municipalities face challenges for sustainable development due to institutional, technical, human, and financial limitations[18,19]. In the State of Mexico, financial capacity is limited by low tax collection and high dependence on federal transfers, limiting its fiscal autonomy[20,21]. In this context, the pig sector is positioned as key to achieving the goals at the political level and in terms of compliance with Sustainability Objectives[19]. This is to better understand trade dynamics, identify economic and social vulnerabilities, and propose strategies that diversify trade relations, promoting a resilient, sustainable, and equitable network. This work seeks to identify the main municipalities that act as origin and destination in the transfer of pigs, as well as to evaluate their centrality, betweenness, and connection patterns within the network.

Material and methods

The analysis of the structure of pig movement was carried out using the Social Network Analysis (SRA) methodology. The network was made up of 125 municipalities in the State of Mexico and 441 municipalities in other states with which relations were established. Four types of markets were analyzed: slaughter, fattening, breeding, and livestock fairs. The data were organized in an adjacency list, where the first column represented the pigs moved according to their origin (x_i) and the second column corresponded to the pigs received according to their destination (x_j). The analysis was carried out at the municipal and intermunicipal levels, incorporating attributes such as the years (2017-2021), the type of movement (origin or destination), the type of market, as well as the degree of centrality and clustering of the nodes.

For data processing, the UCINET software version 6.52 was used, which allowed to identify the hierarchies and roles of participation among the municipalities in addition to calculating mathematical metrics of centrality and betweenness.

The degree of centrality refers to the number of actors with which a node is directly connected[22]. The mathematical equation is defined as follows:

$$d_i = \sum_{i<k<j} \frac{g_{ikj}}{g_{ij}}, \forall_i \in V$$

Where, the formula d_i calculates a value related to the importance or centrality of node i within a network, based on the shortest paths between other nodes passing through i. Specifically, the quotient $\frac{g_{ikj}}{g_{ij}}$ measures the fraction of the shortest paths between i and j that pass through an intermediate node k. The sum over k and j adds these fractions to capture the total impact of node i on all relevant paths in the network.

V: It represents a set of nodes or vertices in a graph. Each element $i \in V$ is a node of the graph. g_{ikj}: It represents a metric associated with the paths in the graph that pass through node K when traveling from node i to node j. It often refers to the number of geodesic paths (the shortest) that include node k. g_{ij}: It is the total number of geodesic paths between nodes i and j regardless of whether they pass through any intermediate node. $\sum_{i<k<j}$: It indicates that the sum is made over all the intermediate nodes k between i and j, respecting the order $i<k<j$. This ensures that only nodes between i and j are considered in the context of the analysis.

The degree of betweenness measures the frequency with which a node is on the shortest paths between other nodes in the network[23]. According to Heredia *et al*[22], the formula is:

$$g_k = \sum_{i<k<j} \frac{g_{ikj}}{g_{ij}}, \forall_k \in V$$

V: It is the set of nodes or vertices in a graph. Each $k \in V$ is a specific node for which this metric is calculated. g_{ikj}: It is the number of shortest paths (geodesic) between nodes i and j that pass through the intermediate node k. This term measures the relevance of k as an intermediary in the connection between i and j. g_{ij}: It is the total number of shortest paths between nodes i and j regardless of whether they pass through k or not. $\frac{g_{ikj}}{g_{ij}}$: This quotient measures the fraction of shortest paths between i and j that pass-through k. If all the shortest paths between i and j pass through k, the value will be 1. If no path passes through k, the value will be 0. $\sum_{i<k<j}$: The sum is made over all pairs of nodes i and j that satisfy the condition $i<k<j$. This ensures that only cases in which k is an intermediate node between i and j are considered. The expression g_k measures the relevance of node k as an intermediary in the shortest paths of the network, quantifying how "central" node k is in terms of its ability to connect other pairs of nodes in the network. If g_k is high, it means that k is involved in many

of the shortest paths between pairs of nodes *i* and *j*, making it a key node for network connectivity.

Pig entry and exit analysis

The indegree and outdegree metrics were analyzed to evaluate the activity of the municipalities in the network. Indegree represents the number of pigs that arrive at a destination municipality, allowing the main distribution points to be identified(24). On the other hand, outdegree indicates the number of pigs that leave a municipality of origin, revealing the main suppliers of pigs within the network(25,26,27). The calculation of the entry and exit averages was performed using the VISONE software version 2.26. This program facilitated the identification of the total volume of pig movement between municipalities, providing a detailed view of the commercial dynamics in the State of Mexico. The formulas used were as follows:

Average indegree

$$\overline{d_\iota} = \frac{\sum_{i=1}^{g} d_{1(n_1)}}{g}$$

$\overline{d_\iota}$: It represents the average indegree of a node (or set of nodes) over *g* configurations. *g*: It is the number of instances, configurations, or situations analyzed. $d_{1(n_1)}$: It is the indegree of node n_1 in a particular configuration *i*. This measures the number of connections directed to n_1 in that instance. $\Sigma_{i=1}^{g}$: It indicates that the values of the indegree $d_{1(n_1)}$ are added together in all *g* configurations. This formula calculates the average indegree of node n_1 through *g* configurations. If *g* represents states over time, this average indicates the degree of connectivity that a node receives, on average, over those states.

Average outdegree

$$\overline{d_o} = \frac{\sum_{i=1}^{g} d_{o(ni)}}{g}$$

$\overline{d_o}$: It represents the average outdegree of a node (or set of nodes) over *g* configurations. *g*: It is the number of instances, configurations, or situations analyzed. $d_{o(n_1)}$: It is the outdegree of node n_1 in a particular configuration *i*. This measures the number of connections directed to n_1 in that instance. $\Sigma_{i=1}^{g}$: It indicates that the values of the outdegree $d_{o(n_1)}$ are added together in all *g* configurations. This formula calculates the average outdegree of node n_1 across *g* configurations. Similar to the case of the indegree, if *g* represents time states, this average indicates how many connections a node directs to others, on average, over time.

Data used

The data used in this study come from official records, with authorization from the National Service for Agrifood Health, Safety, and Quality (SENASICA, for its acronym in Spanish), on the movements of pigs in the State of Mexico from 2017 to 2021. These records included detailed information on the origin and destination of the moved pigs.

The 5-yr temporary coverage allowed us to identify consistent movement patterns, whereas the geographic coverage included all the municipalities of the State of Mexico, as well as those of other states with which they established commercial relations, ensuring a complete representation of the pig network.

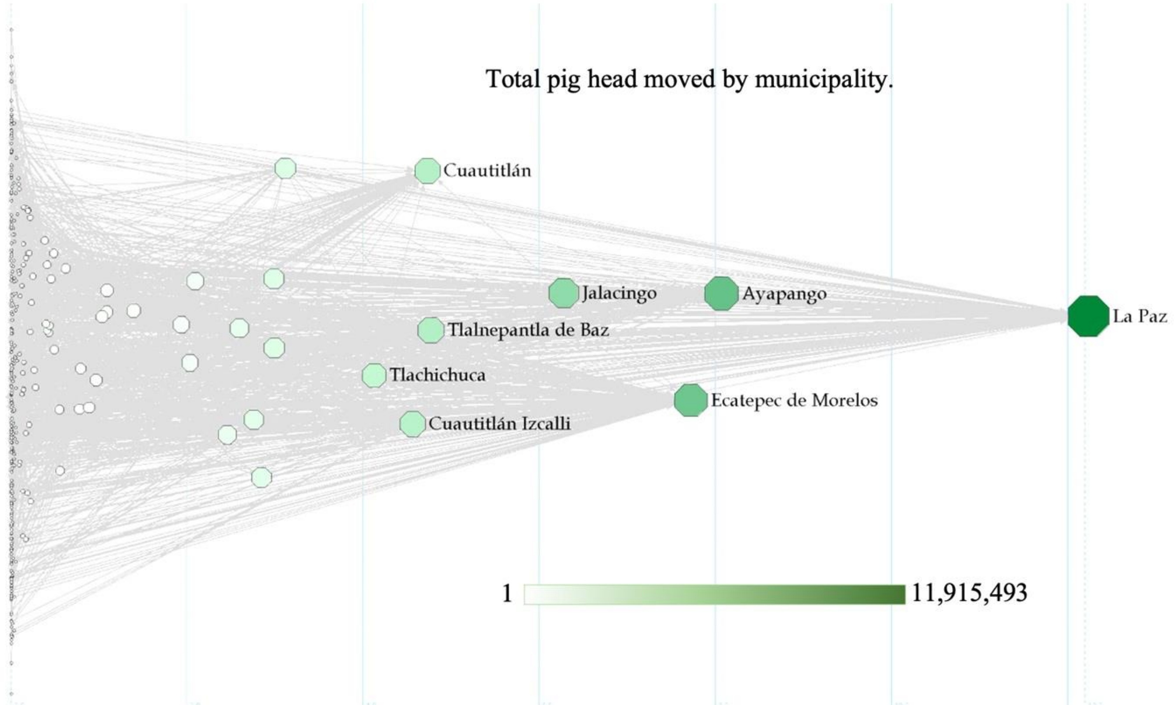
Results and discussion

Between 2017 and 2021, pig transport in the State of Mexico showed a centralized network structure, which can lead to consequences such as increased transport costs due to distance[28] and a significant role in disease transmission[29]. The key municipalities were La Paz, Ayapango, and Cuautitlán Izcalli, which dominate most commercial transactions and act as crucial logistics nodes for the slaughter, fattening, breeding, and livestock fair markets. While this centralization promotes operational efficiency and specialization, it can also generate vulnerabilities to supply disruptions, health outbreaks, or market fluctuations. Economic concentration in certain municipalities can decrease the resilience of supply chains and increase economic inequalities among regions[30,31], which is why the need to diversify trade networks, strengthen transport infrastructure, and promote comprehensive policies that promote balanced economic development, especially in peripheral municipalities with less centrality, is highlighted. A sustainable modernization of infrastructure (Sustainable Development Goals, SDG 9 and 11) could improve the competitiveness of the pig sector, favoring food security and inclusive and sustainable economic growth.

General structure of the network

The pig movement network has direct implications for food security and nutrition. An efficient flow of cattle to key markets ensures a steady supply of meat, an essential component in the diet of the nearly 17 million inhabitants of the State of Mexico[15]. It is estimated that each person in Mexico consumes around 18 kg of pork per year, which translates into a total consumption of approximately 306,000 t per year in the State of Mexico[32]. The pig movement system in the state involved 48.5 million pigs, which indicates that this is a dynamic economic sector, with great potential to generate employment and promote economic growth at the local, municipal, and state levels. Figure 1 summarizes the dynamics of the key municipalities. The main municipalities of origin were Jalacingo, Veracruz (6.28 %); Tlachichuca, Puebla (4.12 %); San Juan de los Lagos, Querétaro (3.11 %); Perote, Veracruz (2.99 %); and Guadalupe Victoria, Puebla (2.98 %), highlighting the presence of industrial farms in these territories. The commercial dynamics with the main receiving municipalities of the State of Mexico are critical since these pigs come from pig consortia with a high concentration of capital. The main destinations were La Paz (12.24 %), Ayapango (8.07 %), Ecatepec de Morelos (7.72 %), Jalacingo (6.28 %), and Tlalnepantla de Baz (4.77 %), which represented a standard concentration of the network[33]. Few strategic municipalities are relevant to the fulfillment of SDG 2 (zero hunger), as they ensure a constant supply of pork, essential for food security[34]. In addition to meeting the demand for meat products, they promote job creation and contribute to local economic growth, highlighting the relevance of the pork sector[35]. Nevertheless, although centralization and connectivity in pig movement can improve meat availability, their impact on hunger eradication is limited. SDG 2 not only seeks to guarantee the supply of food, but also its access to populations in situations of poverty and malnutrition. Pork, although an important source of protein, tends to have a high cost compared to other staple foods, which restricts its consumption among the most vulnerable sectors. In addition, the concentration of production and distribution in a few strategic municipalities could mainly benefit large producers and distributors, without ensuring affordable prices for the population in extreme poverty. For pig movement to effectively contribute to SDG 2, it is necessary to complement their production with strategies that improve equitable access to food and promote affordable and nutritious diets for the neediest communities in the municipalities of the State of Mexico.

Figure 1: Distribution of pig movement in the State of Mexico: Analysis by Municipality



Network connectivity and centralization

The pig network of the State of Mexico was characterized by a low density of commercial relations between municipalities, involving four types of markets (slaughter, fattening, breeding, and livestock fairs) in 229 municipalities of origin and 412 municipalities of destination, out of a total of 2,477 municipalities in the Mexican Republic (Figure 2a.). The average participation in trade relations was 0.002 %, and centralization reached a value of 0.93 %. In terms of pig trade, the most connected municipalities were La Paz, with 68,244 trade relationships, followed by Ayapango (39,454), Ecatepec de Morelos (38,031), Jalacingo (31,908), and Cuautitlán Izcalli (23,430). These municipalities accounted for 37.9 % of the commercial share (Figure 2a.). La Paz and Ayapango stood out for their high connectivity, which highlights the need to improve transportation infrastructure in other municipalities to distribute business opportunities more equitably. Although municipalities such as La Paz and Ayapango have competitive advantages due to their location and level of infrastructure, better connectivity for less advantaged municipalities would allow for more equitable participation in trade, driving more balanced economic growth at the local and regional levels, favoring the fulfillment of SDGs 11 (sustainable cities and communities) and 9 (industry, innovation, and infrastructure).

Betweenness and the role of key municipalities

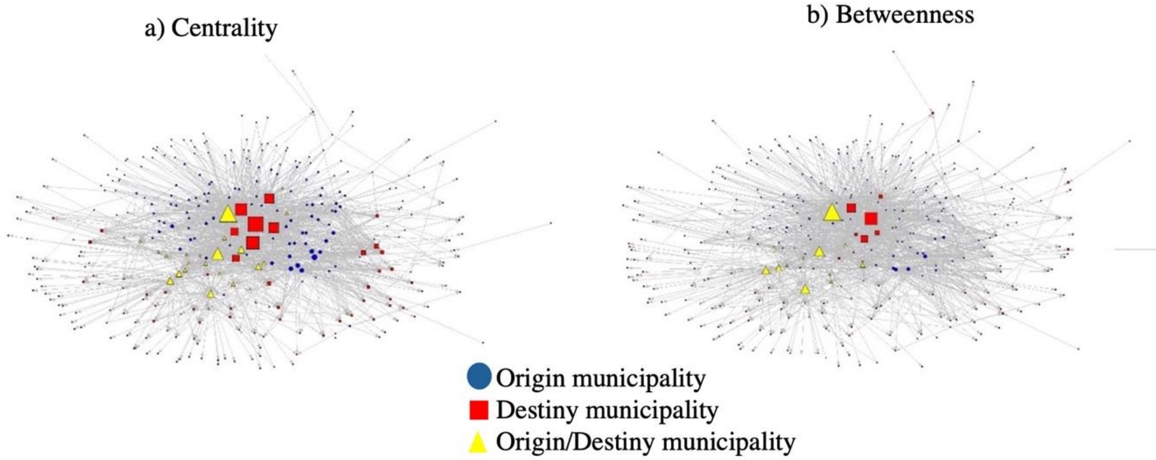
In terms of betweenness, the network showed a centralization index of 10.08 %, reflecting an imbalance in the distribution of commercial relations between municipalities. Cuautitlán Izcalli, with 32,532 commercial relations, was the municipality with the highest betweenness value, acting as a crucial bridge in the pig movement network. Other important municipalities in terms of relationships were Acatlán (20,997) and La Paz (20,010), which played significant roles in connecting diverse municipalities. Nopaltepec, Celaya (Guanajuato), Jilotepec, and Tecámac also presented high betweenness values, varying between 18,367 and 19,223 commercial relations, which indicated that they were essential to maintain connectivity in the network, facilitating the commercial flow of pigs (Figure 2b). The role of logistics hub municipalities highlights the importance of investing in infrastructure that allows a more equitable distribution of commercial activity, reducing pressure on central nodes and promoting more balanced economic development.

Slaughter market dynamics

In the pig slaughter market in Mexico, 48.4 million pigs were moved through 329 municipalities, with a low centralization, of only 1.58 %. This reflects a decentralized network, in which the most relevant municipalities of origin were Jalacingo (12.6 %), Tlachichuca (8.9 %), San Juan de los Lagos (6.7 %), Perote (6 %), and Guadalupe Victoria (6 %). On the other hand, the most important destinations were La Paz (24.5 %), Ayapango (16.2 %), Ecatepec de Morelos (15.5 %), Tlalnepantla de Baz (9.6 %), and Cuautitlán Izcalli (9.5 %) (Figure 2a). This distribution of commercial activities gives municipalities greater autonomy, although it also creates difficulties in the coordination and implementation of integrated economic policies at the state and national levels. The lack of centralization favors economic fragmentation, which can benefit some municipalities over others, limiting equitable access to resources and opportunities[36].

In terms of betweenness, the pig trade showed high degrees of betweenness in Cuautitlán Izcalli (5,353), Jilotepec (4,981), and Tecámac (2,570) (Figure 2b.), suggesting that these municipalities played a crucial role in the slaughter of pigs and in the distribution among various municipalities[37]. This high betweenness implies intense logistical activity that can overload local infrastructures, leading to some critical points in the network facing operational capacity problems. In addition, the infrastructure of the slaughterhouses in municipalities of the State of Mexico has been intensively used, which could lead to negative environmental impacts, such as water pollution and greenhouse gas emissions[38].

Figure 2: Average degree of centralization and betweenness of the municipal pig movement of the State of Mexico in the slaughter market (2017-2021).

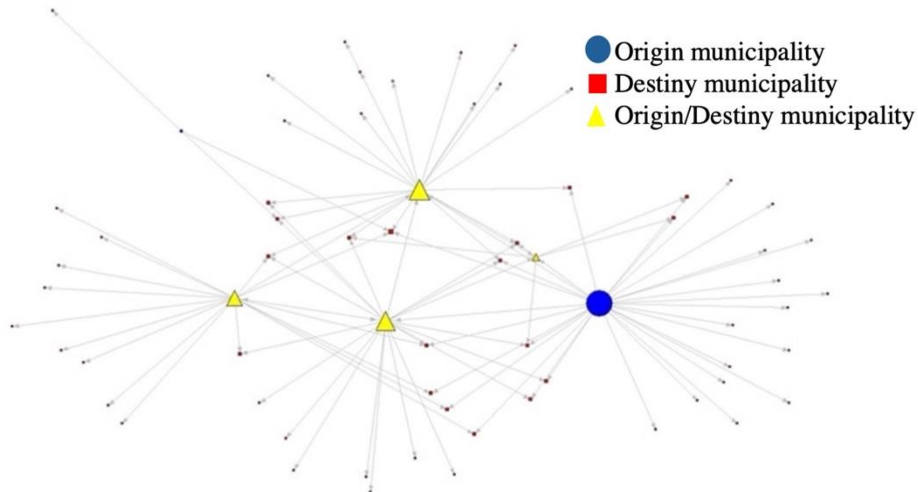


The importance of improving infrastructures and modernizing industries seeks a more effective management of resources and promotes clean technologies and environmentally friendly industrial practices[39], through the modernization of slaughterhouses, prioritizing the use of clean and sustainable technologies, encouraging greater cooperation between municipalities to optimize distribution and reduce economic disparities, and strengthening compliance with environmental and safety regulations[40]. Networks with high betweenness can achieve greater logistical efficiency by integrating modern technologies; however, they also contribute to the concentration of economic power in a few companies, reducing the autonomy of small producers[41]. Decentralized networks, coordinated through cooperatives and producer associations, have managed to balance local autonomy with sustainability and access to international markets[42]. Fragmented systems tend to be less resilient in the face of health and environmental crises, such as African swine fever, underlining the need to integrate modern infrastructure and robust governance policies into decentralized networks[43,44].

Fattening market dynamics

A hierarchical structure with a marked centralization in a few municipalities was observed. Cuautitlán Izcalli and Ecatepec de Morelos stood out as the municipalities with the most relations. The average betweenness value in all municipalities was 6.7, which indicates a notable concentration in those municipalities with low centrality. Most municipalities operated as peripheral nodes with little influence on the configuration of the network, and only a few concentrated the majority of commercial transactions (Figure 3). This type of fattening management is important since many times the small industry does not have the potential to raise and fatten animals in the same place, and they are forced to sell their offspring to be fattened by other actors.

Figure 3: Degree of municipal centralization and betweenness of the pig movement of the State of Mexico in the fattening market



The economic specialization located in certain municipalities, such as Cuautitlán Izcalli, which led the betweenness in the pig marketing network in the fattening market. Specialization can generate advantages in terms of operational efficiency, reducing logistics costs and improving the optimization of resources. Nonetheless, this specialization can also have negative effects on the economic resilience of the municipalities most dependent on a single activity(45,31).

Another key factor influencing the dynamics of the fattening market is the geographical location of municipalities such as Texcoco, Cuautitlán Izcalli, and Ecatepec, which are strategically located near Mexico City, the country's largest consumer market. This geographical proximity reduces transportation costs and improves efficiency in the distribution of pork products, making business operations more profitable. In addition, the proximity to the capital facilitates an active network of communication and trade between producers, intermediaries, and distributors, which promotes more efficient market integration and improves the competitiveness of producers(46).

Policies that support the adaptation of the livestock system to changes in demand can be essential to promote the sustainability of the sector(47). Modernization of infrastructure and the implementation of recent technologies are key factors that can help increase competition and efficiency in the sector, benefiting both producers and consumers(48).

The concentration of pork production in certain regions has kept costs low; nevertheless, it has also generated significant vulnerability to disease outbreaks(49). Specialization in pork production has been a key strategy to increase competitiveness, although diseases can put the system at risk(50).

The increase in demand for fresh, high-quality meats, together with government policies under certain circumstances, could stimulate producers to modify their production systems in response to changes in market demand(47).

Breeding market dynamics

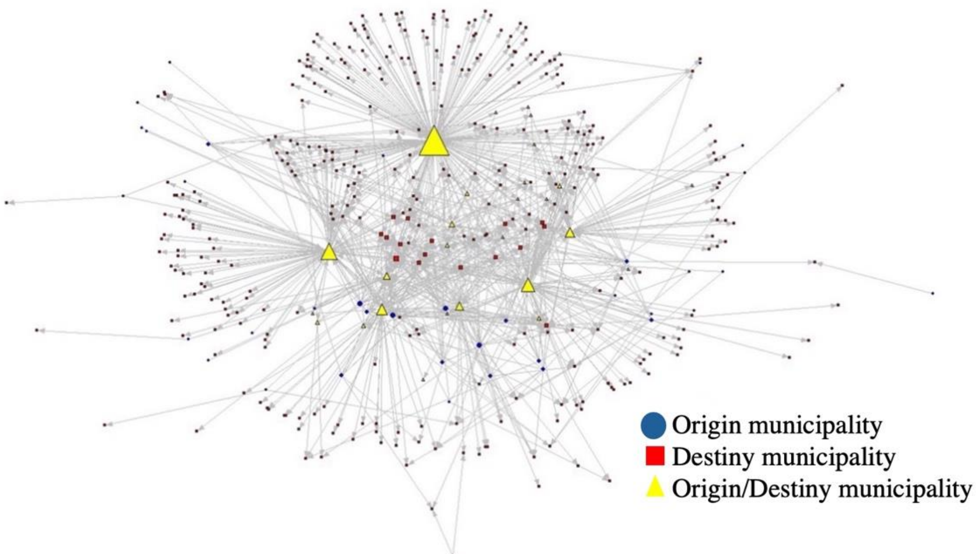
A disparity in structure was observed, which reflected the preponderant role of some municipalities in the movement of pigs for breeding, which is intrinsically related to the pig-breeder social system, which encourages the exchange of genetic material among farmers(51).

Nopaltepec, with 377 commercial relations and a 13.8 % share, ranked as the most important node in the network, followed by Zumpango with 156 connections (5.7 %), Naucalpan de Juárez with 82 (3 %), Jilotepec with 78 (2.9 %), and Cuautitlán Izcalli with 74 (2.7 %) (Figure 4). These municipalities play strategic roles that facilitate the flow of germplasm and stand out as nodes that concentrate commercial relations and maximize logistical efficiency(52).

In addition, the geographical location of these municipalities plays a crucial role in their participation in the network. For example, Nopaltepec and Zumpango, located 46 and 47 km north of Mexico City, respectively, are well connected to the urban market, whereas Naucalpan (20 km northwest) and Cuautitlán Izcalli (32 km northwest) offer quick access to logistics and technology services. This strategic access could not only facilitate the distribution of genetic material, but also allows these municipalities to meet the growing demand for pork efficiently, where proximity to urban markets drives the competitiveness of the agri-food sector(53).

In terms of betweenness, Jilotepec (2,753) and Cuautitlán Izcalli (2,218) stood out as the most influential municipalities (Figure 4). Their role as bridges within the network ensures connectivity, maintains the efficiency and resilience of the pig system, and acts as key stabilizers in similar hierarchical systems(54,55).

Figure 4: Degree of municipal centralization and betweenness of the pig movement of the State of Mexico in the breeding market



The strength of the structure in regional logistics is shown; however, centralization also poses risks, such as dependence on a few municipalities, which can increase vulnerability to interruptions due to logistical, health, or climatic problems, a recurring challenge in centralized livestock networks[56].

Livestock fair market dynamics

The livestock fair market only moved 361 head of cattle during 5 yr in 19 municipalities. Despite this low number, these types of networks tend to be more flexible and sustainable in the long term[57,58].

Abasolo, a municipality in Guanajuato, was key to urban markets, where small producers play essential roles in food value chains[59,60]. Zumpango stood out as the most influential node in terms of betweenness (value of 1), acting as a crucial point for the bidirectional connection between municipalities, fulfilling critical functions without excessively concentrating control of the network[61]. Diversification promotes greater economic stability in local markets and reinforces the importance of maintaining an inclusive and decentralized network[62,63].

The livestock fair market in the State of Mexico has advantageous characteristics in terms of resilience and flexibility. Nonetheless, decentralization can limit access to specialized technological and financial resources[64].

Intermunicipal network

The intermunicipal network in the State of Mexico stands out for its movement capacity and structural balance, integrating municipalities with different levels of participation. It represents a complex system made up of 78 municipalities organized in different roles within the commercialization of pigs. This network facilitated the movement of 64,932 head of cattle, distributed among markets for slaughter (39 municipalities), fattening (26 municipalities), and breeding (66 municipalities). The main nodes included Cuautitlán Izcalli (31.77 %), Jilotepec (24.27 %), and Zumpango (6.72 %), followed by Atizapán de Zaragoza (6.60 %), and Naucalpan de Juárez (5.75 %), which contributed significantly as both origin and destination points. In particular, Jilotepec was the main point of origin for commercialization (33.4 %), whereas Cuautitlán Izcalli stood out as the most relevant destination (36.6 %), evidencing a characteristic pattern of international livestock networks, where the most connected nodes are usually linked to robust logistics infrastructures and proximity to high-consumption urban markets(65).

The network recorded 1,888 connections with a range from 1 to 298, reflecting high connectivity in municipalities such as Naucalpan de Juárez (298), Nopaltepec (235), and Atizapán de Zaragoza (200), who led with a participation of 15.8 %, 12.4 %, and 10.6 %, respectively. Other municipalities with moderate contributions were Xalatlaco, Zumpango, and Cuautitlán Izcalli, with between 190 and 170 connections. Nevertheless, municipalities with lower participation were also integrated, such as San Felipe del Progreso, Apaxco, and Ixtapaluca, which registered only two connections. The relative decentralization of the network, evidenced by a centralization index of 2.09 %, promotes trade flow alternatives and strengthens the resilience of the system, which coincides with previous observations(66), which indicated that distributed connectivity mitigates health and operational risks in livestock networks.

The centrality analysis highlighted Jilotepec as the municipality with the highest degree of betweenness (125 connections), followed by Texcoco(79), Cuautitlán Izcalli (61), Zumpango (41), and Tecámac (19). This type of intermediary plays a key role in the continuity of the trade flow, optimizing transaction costs and facilitating access to markets(67). In addition, municipalities such as Naucalpan de Juárez, Nopaltepec, and Atizapán de Zaragoza, with high connectivity, not only act as mobilization points, but also as platforms for the redistribution of livestock to other areas of the network, which reflects essential patterns for the sustainability of supply chains in areas with high population density(68).

The need to strengthen infrastructure in peripheral municipalities, improve traceability systems, and promote intermunicipal collaboration is evident, contributing to the sustainable development of the pig sector and mitigating risks associated with livestock networks. Given that these records correspond only to the movements documented by SENASICA, the main limitation of the study is that it does not include small-scale farms, a production system widely present in the State of Mexico and with a particular dynamic[51]. Likewise, this study does not consider costs, economic variables, or aspects of animal welfare or environmental impact despite the fact that this information is fundamental in the analysis of animal production systems.

Conclusions and implications

The movement of pigs in the State of Mexico was highly centralized in a limited number of municipalities that act as essential logistics nodes, facilitating the flow of pigs to key markets and ensuring a supply of pork. However, the concentration of trade relations in a few municipalities could generate critical economic dependence, which represents a vulnerability to possible interruptions in the supply network, affecting both food security and the economic stability of the territories. Network centralization can boost employment and economic growth in the best-connected municipalities, but it limits development opportunities and widens economic inequalities, especially in sectors that rely on efficient infrastructure for transport and the marketing of goods. The production and transport of pigs are not primary economic activities in all peripheral municipalities. The reliance on a few municipalities poses significant risks in the event of economic crises or disruptions to the pig network of the State of Mexico, exposing the supply chain to bottlenecks that could have severe repercussions if any of these key nodes face problems, such as natural disasters or lack of resources. Therefore, it is imperative to promote policies that encourage economic diversification and the redistribution of commercial activity among more municipalities, which would reduce dependence and increase the economic resilience of the pig network in the State of Mexico. The fragmentation observed in the network highlights the need for greater coordination between municipalities and between the state and federal levels. A more efficient integration, based on joint planning and a better connection between these actors, would make it possible to optimize resources, improve infrastructure, and reduce regional inequalities. This requires aligned public policies that promote balanced development, prioritizing the most disadvantaged regions without neglecting those already connected.

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Literature cited:

1. FAOSTAT. Crops and livestock products. 2024. https://www.fao.org/faostat/en/#data/QCL.

2. OECD/FAO. Agricultural Outlook 2024-2033. Paris: OECD Publishing; 2024. https://doi.org/10.1787/4c5d2cfb-en.

3. Babot D, Casaponsa J, Santamarina C, Hernández-Jover M, Gallardo J. Lectura dinámica de cerdos en crecimiento utilizando tecnología electrónica. FAO. 2004. https://agris.fao.org/search/es/records/64725154e17b74d2224fce1c.

4. Huerta-Silva HD, Giraldi-Díaz MR, Castillo-González E. Evaluación de los impactos ambientales asociados a la producción intensiva de cerdos en México. 2023. https://pecuarios.com/biblioteca-digital-issn/publicacion/vol-1/num-1/evaluacion-de-los-impactos-ambientales-asociados-a-la-produccion-intensiva-de-cerdos-en-mexico.

5. SIAP. Panorama Agroalimentario 2018-2024. México. 2024. https://drive.google.com/file/d/1NXcDhaB63Z94wjRUVF6f_FK0Urv6cgvJ/view.

6. USDA ERS. Sector at a glance. 2024. https://www.ers.usda.gov/topics/animal-products/hogs-pork/sector-at-a-glance/#Loc1.

7. Genesus. World Mega Producer. 2024. https://email.envoke.io/web_files/544/2024%20World%20Mega%20Producer.pdf?t=1717334298891.

8. INEGI. Censo Agropecuario 2022. Resultados definitivos. https://www.inegi.org.mx/contenidos/programas/ca/2022/doc/ca2022_rdnal.pdf .

9. Bobadilla-Soto EE, Rebollar-Rebollar S, Rouco-Yáñez A, Martínez-Castañeda FE. Determinación de costos de producción en granjas productoras de lechón. Rev Mex Agroneg 2013;32:268-79.

10. Tinoco J, Juárez N. El impacto del crédito en la producción ganadera de México, de 2010 a 2019. Rev Mex Agroneg 2024; 54:589-98. https://doi.org/10.22004/ag.econ.344560.

11. Martínez-Castañeda FE, Perea-Peña M. Estrategias locales y de gestión para la porcicultura doméstica en localidades periurbanas del Valle de México. Agric Soc Desarro. 2012;9(4):411-25. https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1870-54722012000400003.

12. Figueroa-Sandoval B, Mora-Flores JS, Fuentes-Palomino DG. Factores que influyen en la inclusión financiera de los porcicultores en México. Rev Mex Agroneg 2022;56:116.

13. Sosa-Urrutia ME, Martínez-Castañeda FE, Espinosa-García JA, Buendía-Rodríguez G. Contribución del sector pecuario a la economía mexicana. Un análisis desde la Matriz Insumo Producto. Rev Mex Cienc Pecu 2017;8(1):31-41. https://doi.org/10.22319/rmcp.v8i1.4308.

14. CPEUM. Constitución publicada en el Diario Oficial de la Federación el 5 de febrero de 1917. Texto vigente con última reforma publicada el 15 de septiembre de 2024. Diario Oficial de la Federación. https://www.gob.mx/cms/uploads/attachment/file/966422/Constitucion_Politica_de_los_Estados_Unidos_Mexicanos.pdf.

15. INEGI. Censo de Población y Vivienda 2020. https://www.inegi.org.mx/programas/ccpv/2020/.

16. SIAP. Producción pecuaria porcina por entidad federativa y año. 2022. https://www.gob.mx/siap.

17. Callejas-Juárez N, Salas-González JM. Estructura de la red de mercado de bovinos en México, 2017-2021. Rev Mex Cienc Pecu 2023;14(4):745-59. https://doi.org/10.22319/rmcp.v14i4.6433.

18. INAFED. Grandes retos en el ámbito municipal para implementar la Agenda 2030. Gobierno de México. 2018. https://www.gob.mx/inafed/articulos/grandesretos-en-el-ambito-municipal-para-implementar-la-agenda-2030.

19. Gobierno de México. La Agenda 2030 y el desarrollo municipal sostenible: Guía para la elaboración de planes municipales de desarrollo con el enfoque de la Agenda 2030. 2020. https://www.gob.mx/cms/uploads/attachment/file/590381/Gu_a_Planes_Municipales_Sostenibles_VF.pdf.

20. Ibarra-Salazar J, González H, Sotres-Cervantes L. Aspectos políticos de la dependencia financiera en los municipios mexicanos. RMCPyS. 2013;58(217):139-170. https://doi.org/10.1016/S0185-1918(13)72278-5.

21. Madrigal-Delgado GJ, Bueno-Cevada LE. Transferencias, gestión fiscal municipal y la desigualdad interregional en México. Investig Adm 2019;48(124):1-17.

22. Heredia-Sánchez MG, Martínez-Castañeda FE, Ruiz Torres ME, González-Hernández V, Nuñez-Espinoza JF, Thomé Ortíz H. Social interactions and business portfolio among vegetable producers in central Mexico. Agro Productividad 2023. https://doi.org/10.32854/agrop.v15i4.2394.

23. Freeman L. A set of measures of centrality based upon betweenness. Sociometry 1997;40(1):35-41. https://doi.org/10.2307/3033543.

24. Wasserman S, Faust K. Social network analysis: methods and applications. 1st ed: Cambridge University Press; 1994. https://doi.org/10.1017/CBO9780511 815478.

25. Newman M. Networks: An Introduction. Oxford: Oxford University Press; 2010. https://doi.org/10.1093/acprof:oso/9780199206650.003.0002.

26. Brualdi-Richard A. Clases de matrices combinatorias. In: Enciclopedia de matemáticas y sus aplicaciones, vol. 108. Cambridge: Cambridge University Press; 2010. https://doi.org/10.1017/CBO9780511721182.

27. Satyanarayana B, Prasad KS. Matemáticas discretas y teoría de grafos. New Delhi: PHI Learning Pvt. Ltd.; 2014.

28. Heinrichs J, Kuhn T, Pahmeyer C, Britz W. Economic effects of plot sizes and farm-plot distances in organic and conventional farming systems: A farm-level analysis for Germany. Agric Syst 2021;187:102992. https://doi.org/10.1016/j.agsy.2020.102992.

29. Ferdousi T, Moon SA, Self A, Scoglio C. Generation of swine movement network and analysis of efficient mitigation strategies for African swine fever virus. PLoS One. 2019;14(12):e0225785. https://doi.org/10.1371/journal.pone.0225785.

30. Perry BD, Randolph TF, Ashley S, Chimedza R, Forman T, Morrisson J, Poulton C, Sibanda L, Stevens C, Tebele N, Yngström I. The impact and poverty reduction implications of foot and mouth disease control in southern Africa, with special reference to Zimbabwe. Nairobi: International Livestock Research Institute (ILRI); 2003. https://www.researchgate.net/publication/267973759_The_Impact_and_Poverty_Reduction_Implications_of_Foot_and_Mouth_Disease_Control_in_Southern_Africa_with_Special_Reference_to_Zimbabwe.

31. Feldman, MP. Location and innovation: the new economic geography of innovation, spillovers, and agglomeration. In: Clark GL, *et al*.editors. The Oxford Handbook of Economic Geography, Oxford University Press, Oxford. 2000;373-394. https://www.academia.edu/734077/Location_and_innovation_the_new_economic_geography_of_innovation_spillovers_and_agglomeration.

32. SADER. El cerdo, base culinaria en México. 2020. https://www.gob.mx/agricultura/articulos/el-cerdo-base-culinaria-en-mexico.

33. Shi F, Huang B, Shen C, Liu Y, Liu X, Fan Z, Mubarik S, Yu C, Sun X. Characterization and influencing factors of the pig movement network in Hunan Province, China. Prev Vet Med 2021;193:105396. https://doi.org/10.1016/j.prevetmed.2021.105396.

34. Herranz A. Sector porcino: sostenibilidad, seguridad alimentaria y bienestar animal. ANAPORC. 2019;16(158):44-45. https://dialnet.unirioja.es/servlet/articulo?codigo=6793225.

35. ONU-CEPAL. La Agenda 2030 y los Objetivos de Desarrollo Sostenible: una oportunidad para América Latina y el Caribe (LC/G.2681-P/Rev.3), Santiago. 2018. https://repositorio.cepal.org/server/api/core/bitstreams/cb30a4de-7d87-4e79-8e7aad527903 8718/content.

36. Puebla MA. Análisis de la desigualdad económica municipal del estado. Actualidad Económica 2021;31(105)37-48.

37. Signorini PM, Civit GS, Bonilla PM, Cervantes RME, Calderón VM, Pérez MA, Espejel MMP. Evaluación de riesgos de los rastros y mataderos municipales. México, D.F. https://www.gob.mx/cms/uploads/attachment/file/154388/Evaluacion_de_riesgos_de_los_rastros_y_mataderos_municipales.pdf.

38. Coordinación de Regulación Sanitaria. Buenas prácticas de manufactura e higiene para rastros y unidades de sacrificio o mataderos municipales y privados. 2024. https://salud.edomex.gob.mx/isem/docs/regulacion_sanitaria/bienesyservicios/007.pdf.

39. ONU. Meta 9.4: Modernización de infraestructuras e industrias sostenibles. Agenda 2030 para América Latina y el Caribe, 2025. https://agenda2030lac.org/es/ods/9industria-innovacion-e-infraestructura/metas/94.

40. Pichardo Pagaza I. Responsabilidades municipales en materia ambiental. Convergencia. Rev Cienc Soc 2009;16(49):291-308.

41. USDA ERS. Sector at a glance. 2024. https://www.ers.usda.gov/ topics/animal-products/hogs-pork/sector-at-a-glance/#Loc1.

42. FAO. Ministerio de Medio Ambiente y Alimentación de Dinamarca, Administración Danesa de Veterinaria y Alimentación. Hacer frente al uso de antimicrobianos y la resistencia a los antimicrobianos en la producción porcina: lecciones aprendidas de Dinamarca. Roma; 2019.: https://www.fao.org/3/ca5567es/ca5567es.pdf.

43. Asian Development Bank. Asia's infrastructure needs exceed $17 trillion per year, double previous estimates. 2017. https://www.adb.org/es/news/asia-infrastructure-needs-exceed-17-trillion-year-double-previous-estimates?utm_source.

44. Viljoen G. Las autoridades de Viet Nam controlan la propagación de la peste porcina 743 africana mediante técnicas nucleares. OIEA; 2020. https://www.iaea.org/sites/default/files/6122525es.pdf.

45. Perry BD, Grace D, Sones K. Current drivers and future directions of global livestock disease dynamics. Proc Natl Acad Sci 2011;110(52):20871-20877. https://doi.org/10.1073/pnas.1012953108.

46. Porter ME. The competitive advantage of nations. Free Press; 1990. https://scispace.com/pdf/the-competitive-advantage-of-nations-2puz3hhknn.pdf.

47. FAO. World Livestock: Transforming the livestock sector through the Sustainable Development Goals. 2018. https://openknowledge.fao.org/server/api/core/bitstreams/3e7 ba7ed-1eb1-48cf-8792-ae4773e9a79b/content.

48. OECD. Innovation, productivity and sustainability in food and agriculture: Main Findings from Country Reviews and Policy Lessons. OECD Food and Agricultural Reviews, OECD Publishing, Paris; 2019. https://doi.org/10.1787/c9c4ec1d-en.

49. Barcellos M, Saab MS, Perez-Cueto F, Perin M, Neves M, Verbeke W. Pork consumption in Brazil: Challenges and opportunities for the Brazilian pork production chain. J Chain Network Sci. 2011;11:99-113. https://doi:10.3920/JCNS2011.Qpork3.

50. Piao S, Jin X, Hu S, Lee J-Y. The impact of African swine fever on the efficiency of China's pig farming industry. Sustainability 2024;16(7):7819. http://doi:10.3390/su16177819.

51. Santos-Barrios L, Núñez-Espinoza JF, Ruiz-Torres ME, Clava-Hernández T, Martínez García CG, Martínez-Castañeda FE. Strategies and socio-productive relationships in pig backyard production. Agro Productividad 2021;14(12):29-40. https://doi.org/10.32854/agrop.v14i12.1990.

52. Villalba F, Afanador Barajas J. Sistemas Logísticos en la comercialización de productos agrícolas basados en la industria 4.0. 2022. https://repositoriocrai.ucompensar.edu.co/bitstreams/b16b2b99-7f3c-4598-b4d8-772d9e8fc63fb6e/download.

53. Amat Llombart P. Sistemas alimentarios locales y producción agroalimentaria de proximidad. Su funcionalidad en la protección de tierras agrícolas. Rev Esp Estud Agrosoc Pesqueros 2024;263:287-317. https://doi.org/10.24197/reeap.263.2024.287-317.

54. Borgatti SP, Everett MG. Models of core/periphery structures. Soc Netw 2000;21(4):375-395. https://doi:10.1016/S0378-8733(99)00019-2.

55. Uddin KS, Atanasova KR, Krueger WS, Ramirez A, Gray GC. Epidemiology, geographical distribution, and economic consequences of swine zoonoses: a narrative review. Emerg Microbes Infect 2013 Dec;2(12):e92. https://doi.org/10.1038/emi.2013.87.

56. Beltran-Alcrudo D, Falco JR, Raizman E, *et al*. Transboundary spread of pig diseases: the role of international trade and travel. BMC Vet Res 2019;15:64. https://doi.org/10.1186/s12917-019-1800-5.

57. Adger WN. Social and ecological resilience: are they related? Prog Hum Geogr. 2000;24(3):347-364. https://doi.org/10.1191/030913200701540465.

58. Ellis F. Rural livelihoods and diversity in developing countries. Oxford: Oxford University Press; 2023. https://doi.org/10.1093/oso/9780198296959.001.0001.

59. Pingali P. Agricultural growth and economic development: a view through the globalization lens. Agric Econ 2007;37:1-12. https://doi.org/10.1111/j.1574-0862.2007.00231.x.

60. Reardon T, Swinnen J, Barrett C, Berdegué J. Agrifood industry transformation and small farmers in developing countries. World Dev 2009;37:1717-1727. https://doi.org/10.1016/j.worlddev.2008.08.023.

61. Coordinadora Europea Vía Campesina. Ganadería en Europa: apoyar una transición ambiciosa hacia modelos campesinos. Bruselas; 2023. https://www.eurovia.org/wp-content/uploads/2023/02/ECVC-2023-ESP-Ganaderia.pdf.

62. Ostrom E. Governing the Commons: The evolution of institutions for collective action. Cambridge: Cambridge University Press; 1990. https://doi.org/10.1017/CBO9781316423936.

63. Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, Rockström J. Resilience thinking: integrating resilience, adaptability and transformability. Ecol Soc 2010;15(4):20. http://www.ecologyandsociety.org/vol15/iss4/art20/.

64. Schejtman, A, Berdegué JA. Desarrollo territorial rural. RIMISP. 2004. https://rimisp.org/wpcontent/files_mf/1363093392schejtman_y_berdegue2004_desarrollo_territorial_rural_5_rimisp_CArdumen.pdf.

65. FIDA. Cómo efectuar una evaluación rápida del mercado ganadero: Guía para profesionales. 2019. https://www.ifad.org/documents/48415603/49809039/htdn_livestock_market_s.pdf/02c5e342-dc83-fd1e-a01e-00ea5e82dcef?t=1726643242089.

66. Callejas-Juárez N. Mercado de bovinos para engorda en México: un enfoque de redes. Rev Agronomía Mesoam. 2024;35:54741. https://doi.org/10.15517/am.2024.54741.

67. Aguilar-Rodríguez HE. Buenas prácticas en la ganadería bovina. Petroglifos. Rev Crít Transdisciplinar 2024;7(2):e070201. https://doi:10.5281/zenodo.14028472.

68. Gómez MJ. Las cadenas de suministro y el desarrollo sostenible: una revisión de la literatura. Ruta 2023;20:1089. https://doi.org/10.15443/RUTA20231089.