



## Invited Review [Revisión]

**A BRIEF UPDATE ON SHEEP PRODUCTION IN MEXICO:  
CHALLENGES AND PROSPECTS †**
**UNA BREVE ACTUALIZACIÓN SOBRE LA PRODUCCIÓN OVINA EN  
MÉXICO: RETOS Y PERSPECTIVAS**

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**SUMMARY**

**Background:** Looking towards 2050, substantial increases in agricultural productivity are needed to meet the projected demands of the growing world population. Inevitably, profound changes will occur in the sheep production systems and Latin-American countries such as Mexico will need to adapt to these changes. **Objective:** To provide a brief update on sheep production in Mexico and discuss the current challenges and prospects. **Main findings:** The development of the Mexican sheep sector is relatively slow since it is affected by complex factors including social, political, and economic changes that impact sheep production, and consumption of sheep products, as well as the diverse type of production systems throughout the country. Extensive production systems in Mexico are associated

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with limitations but have the potential for improvement in areas such as nutrition management, breeding programs, and response to consumer perception trends. In this regard, integrated efforts should be made to enhance sheep productivity in Mexico. **Implications:** The analysis was limited only to scientific contributions explored. An analysis that considered other sources of information could have strengthened this analytical exercise. **Conclusion:** The sheep industry in this country will concurrently face with two challenges related to increasing production efficiency: a) sheep production aimed to keep sustainability and animal welfare, and b) production of by-products, considering product quality, differentiation, value added, and marketing. Lastly, Mexican sheep production will require to consider the animal, social, and farming systems that together promote sustainable production.

**Keywords:** Mexico; Sheep Production; Small Ruminants; Sustainable development; Welfare.

## RESUMEN

**Antecedentes:** Mirando hacia 2050, se necesitan aumentos sustanciales en la productividad agrícola para satisfacer las demandas proyectadas de la creciente población mundial. Inevitablemente, ocurrirán cambios profundos en los sistemas de producción ovina y los países latinoamericanos como México deberán adaptarse a estos cambios.

**Objetivo:** Brindar una breve actualización sobre la producción ovina en México y discutir los desafíos y perspectivas actuales. **Principales hallazgos:** El desarrollo del sector ovino mexicano es relativamente lento ya que se ve afectado por factores complejos que incluyen cambios sociales, políticos y económicos que impactan la producción ovina y el consumo de productos ovinos, así como los diversos tipos de sistemas de producción a lo largo del país. Los sistemas de producción extensiva en México están asociados con limitaciones, pero tienen potencial de mejora en áreas como el manejo de la nutrición, los programas de mejoramiento y la respuesta a las tendencias de percepción del consumidor. En este sentido, se deben realizar esfuerzos integrados para mejorar la productividad ovina en México.

**Implicaciones:** El análisis se limitó únicamente a las contribuciones científicas exploradas. Un análisis que considerara otras fuentes de información podría haber fortalecido este ejercicio analítico. **Conclusión:** La industria ovina en este país enfrentará simultáneamente dos desafíos relacionados con el aumento de la eficiencia productiva: a) la producción ovina orientada a mantener la sustentabilidad y el bienestar animal, y b) la producción de subproductos, considerando la calidad del producto, la diferenciación y el valor agregado, y mercadeo. Por último, la producción ovina mexicana requerirá considerar los sistemas animal, social y ganadero que en conjunto promuevan la producción sustentable.

**Palabras clave:** México; Producción; Ovejas; Sostenibilidad; Bienestar.

## INTRODUCTION

Globally, small ruminant production plays an important socio-economic and ecological role (Simões *et al.*, 2021; Montossi *et al.*, 2013). In developing countries, the importance of small ruminants for human well-being in terms of nutrition and income cannot be unnoticed (Morris, 2017; Simões *et al.*, 2021). Sheep (*Ovis aries*) were among the original domesticated animal species and played an important role in the early stages of civilization and livelihood of human populations in developing countries (Morris, 2017).

The main regions of sheep production are found within the latitudes 35–55° north in Asia and Europe and between 30–45° south in Australia, New Zealand, and South America (Simões *et al.*, 2021). These are temperate regions of the world with great pasture conditions which make up over 60% of the world's sheep population. The annual world sheep meat production accounts for approximately 3% of global meat production (Morris, 2017). However, sheep have different adaptation mechanisms such as their coat that uniquely makes them productive in hot, semi-hot, and humid environments (Montossi *et al.*, 2013; Morris, 2017). After a decline in global sheep supply over the last decades, Montossi *et al.* (2013) emphasized that

sheep will regain market share, coupled with price incentives relative to other animal products.

In Latin America, the major sheep producers with the largest number of heads are Brazil, Argentina, Peru, Bolivia, and Mexico (Robles-Jimenez *et al.*, 2022). In Mexico, these animals are mostly used for meat, wool, and dairy. However, the geographic condition, as well as the availability of grassland and pasture is a feature of sheep farms in Mexico that determines the productive purpose leading to different production systems varying between geographical areas (Robles-Jimenez *et al.*, 2022; Hernández-Marín *et al.*, 2017). In Mexico, currently, over 8 million sheep are produced with the large distribution (about 50%) found in five states namely, Mexico, Hidalgo, Veracruz, Oaxaca, and Puebla with 15.9%, 13.4%, 8.1%, 6.1%, and 5.5% of total sheep population, respectively (Hernández-Marín *et al.*, 2017). Generally, in these states, the production systems are recognized by their low adoption of new technologies and management related to nutrition, reproduction, preventive health, and genetics.

In Mexico, the sheep sector is important in locations with abundance of local grasses and forages (Robles-Jimenez *et al.*, 2022; Parsons *et al.*, 2011). However, there are serious challenges related to the integration of

value chain (i.e., production, processing, and marketing) of sheep products. From the consumer view, there is a growing concern about the sustainability of intensive livestock production owing to its environmental potential, health, and welfare issues (Miranda-de la Lama *et al.*, 2017). Not less importantly, in Mexico, published studies concerning the state-of-the-art of sheep production are unusual and documenting sheep production issues and future viewpoints could be of great value, not only for sheep producers, but also for the rest of the sheep value chain including those players from industry, research, retail, and marketing.

This review aims to provide insights into the sheep production in Mexico and discuss its current challenges and future perspectives. To do so, three specific objectives are pursued: 1) to provide the status of the sheep sector in Mexico; 2) to identify the main health, welfare, and environmental issues related to sheep farming; and 3) to define future challenges and opportunities through addressing gaps in knowledge within the Mexico sheep sector to direct future research efforts.

### ORIGIN OF SHEEP PRODUCTION IN MEXICO

An animal production system reflects different dimensions; therefore, this section provides some historic context about the origin of sheep production in Mexico. The first livestock that was introduced in large numbers to New Spain (today's Mexico) was the pig, due to its ease of transport, reproduction, and prolificacy, and sheep were introduced soon after the conquest, at least as early as 1525 (García Martínez, 1994). The surrounding regions of what is now known as Mexico City were granted to settlers temporarily, without permission to build stone houses or plant crops and keep the pastures in common, according to the old Castilian custom. The indigenous people were the main agricultural producers during the 16<sup>th</sup> century, and the Spanish were the main ranchers. The expansion of livestock caused the dislocation of the self-sufficient indigenous agricultural system, causing famine effects at the end of the 16<sup>th</sup> century. Cattle did not expand until the vast northern territories were conquered. The first meat market was organized around 1524 and it was a Spanish institution since the indigenous people were not used to eating meat, these markets were fully regulated and in the case of sheep, there were complaints that mutton was being sold as castrated mutton, which was more expensive and thus, the butcher was forced to announce the type of ram that he would sell.

### SHEEP PRODUCTION IN THE MEXICAN ECONOMY

Unlike other Latin-American and European countries, sheep production in Mexico is mostly related to one dish called *Barbacoa* and its importance in the economy will be revised in this section. Below some global and regional aspects of sheep production will be discussed.

By 2050 world's meat production will increase by 19% (57.7 million tons), and sheep meat production will increase by 3.8 million tons (Simões *et al.*, 2021). The Asian, American, and African continents will be the ones to increase such production, in this context the American continent concentrates the least number of sheep worldwide (7.2%) with more than 87 million live sheep, compared to Oceania (8.47%), Europe (10.7%), Africa (28.1%), and Asia (45.4%). The American countries with the largest number of sheep are Brazil followed by Argentina, Peru, Bolivia, and Mexico (Calderón-Cabrera *et al.*, 2022), the later is in the 31<sup>st</sup> position worldwide for sheep meat production (Gabriel-Véjar *et al.*, 2022). According to growth rates, the sheep population is not sufficient to supply the demand for sheep products. Mexico slaughtered 36% of the total sheep inventory in 2019 (Robles-Jimenez *et al.*, 2022) and that continues to be a productive deficiency in the flocks as pointed out earlier by De Lucas-Trón and Arbiza-Aguirre (2006). From 1980 to 2019, sheep production in Mexico had great changes because of the decrease in the use of wool as a natural textile fiber and the increased in demand for sheep meat (Robles-Jimenez *et al.*, 2022).

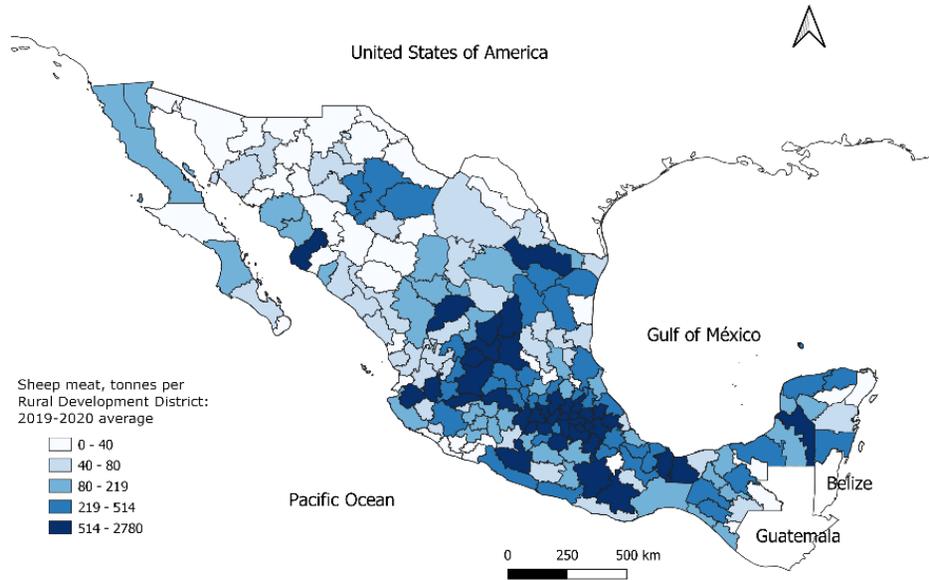
The geographical distribution of sheep is concentrated around the central zones of the country, where sheep meat is mainly consumed. On the other hand, per capita consumption has decreased in recent years, probably because of the Mexican economic situation and the almost exclusive consumption of meat in the form of *Barbacoa* (Robles-Jimenez *et al.*, 2022), therefore, it is imperative to find new ways to incorporate sheep meat into the Mexican culinary culture, so that it is an economical option for consumption.

The public policies implemented, such as support for national repopulation and the reinforcement of the sheep product value chain, have led to reduce sheep meat imports (Robles-Jimenez *et al.*, 2022), however, there is not much information on the effects of this on production efficiency, since in the last 10 years the growth in national production has been lowered. An area of opportunity is seen in the export of Mexican genetics, as well as lamb carcasses for Latin American and Asian markets. It is important to note that there are no official statistics on sheep's milk production in Mexico, and the data from FAO Statistical Database (FAO, 2021) are

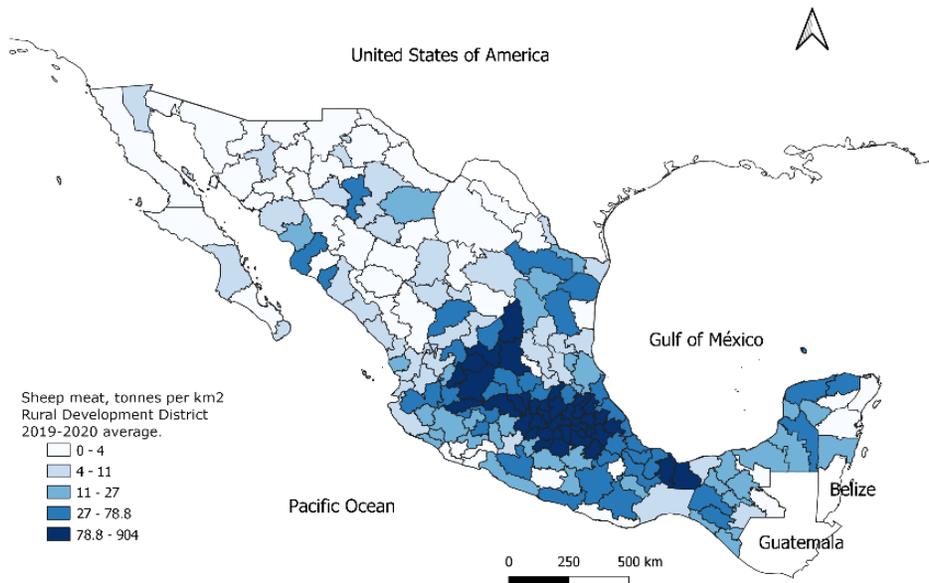
only estimates. There are no more than 100 milk producers in Mexico, and most of them concentrated in Querétaro and the State of Mexico (Robles-Jimenez *et al.*, 2022).

In Mexico, the center of the country is the main production pole for sheep meat, and that extends to the

north through Zacatecas, San Luis Potosí, and Durango (Figure 1-2). These are temperate and semi-arid zones close to market centers. The tropical zones have less production, although pushed by the demand of touristic zones of the southeast, which has led to development of more areas production.



**Figure 1.** Sheep meat per Rural Development District (average production from 2019-2020). Based on data from Servicio de Información Agroalimentaria y Pesquera, Secretaría de Agricultura, Ganadería y Desarrollo Rural, México (2023). The figure is the original work of the authors.



**Figure 2.** Sheep meat per km<sup>2</sup> Rural Development District (average production from 2019-2020). Based on data from Servicio de Información Agroalimentaria y Pesquera, Secretaría de Agricultura, Ganadería y Desarrollo Rural, México (2023). The figure is the original work of the authors.

Regarding wool, its production is concentrated in the center of Mexico (Figure 3). Another production pole is further north, in San Luis Potosí, Zacatecas, and Durango. To the south, there are two important poles: Oaxaca and Chiapas. The latter is closely associated with clothing manufacturing of the original ‘Tzotzil’ communities, mainly manufactured by women. This represents a net annual income of 40% for indigenous families (Perezgrovas *et al.*, 1994). This community conserves endemic sheep of the ‘Chiapas’ breed only for wool production since for traditional and religious reasons it is prohibited to slaughter or consume sheep meat. The rest of the wool is destined to produce hand crafted garments.

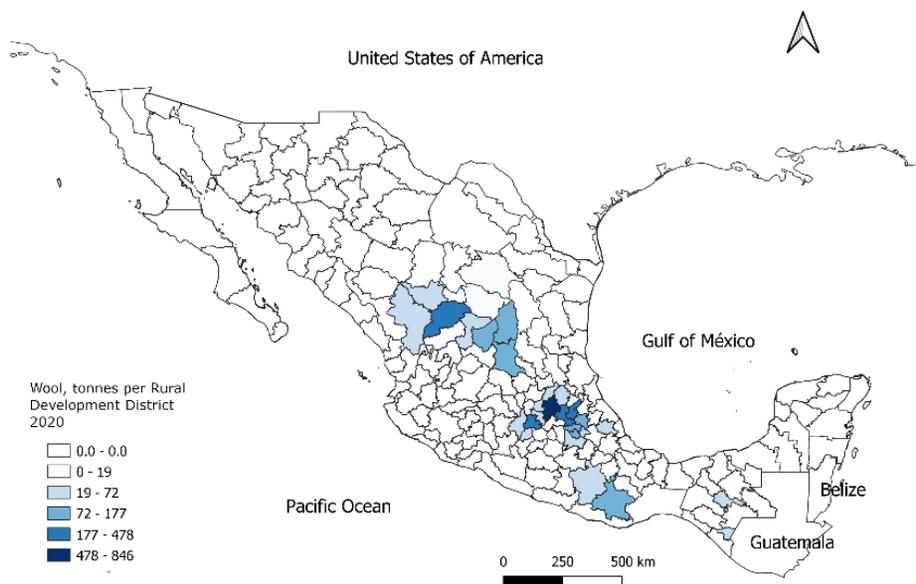
Until now, the central region of Mexico has the greatest opportunity for development since feedstuffs and the meat market for *Barbacoa* are readily available. As observed in Figures 1, 2 and 3., sheep production in Mexico is characterized and differentiated by regions. The north is based on wool and meat production systems; the central region, which produces crossbreeding (Suffolk or Hampshire and hair sheep), is carried out in marginalized areas, in rangelands and on agricultural land with agricultural residues. The southern and southeastern regions have tropical characteristics where hair sheep breeds (Pelibuey and Black Belly) are notable and recently specialized breeds for meat production (Dorper and Katahdin) have been incorporated.

## SHEEP PRODUCTION SYSTEMS

This section is intended to provide an overview of the sheep production systems that could be found in Mexico. Due to the diversity in ecosystems and size of Mexico, there will be different production systems, and this will be discussed below.

In Mexico, there are two types of producers based on their economic capacity, where the ‘small producer’ is characterized by owning a few numbers of heads, most of these producers do not have land for grazing and carry out this activity for self-consumption (Bobadilla-Soto *et al.*, 2014) (Figure 4). The other type of producer is ‘the enterprise’, dedicated to the production of sheep for the supply and breeding of high genetic improvement, which is characterized by having large flocks, with hired labor, technical advice, and access to financing sources (Bobadilla-Soto *et al.*, 2015) (Figure 5).

Sheep farming in Mexico is developed under a regional scheme, in the central zone of the country commonly known as marginalized areas, meat, and skins are produced with wool breeds (including Suffolk, Hampshire, Rambouillet, and Dorset) and hair breeds (including Katahdin, Dorper, and Pelibuey) (Mondragón-Ancelmo *et al.*, 2012). The south and southeast zone with tropical areas is mainly oriented to meat production with hair breeds (including Pelibuey, Black Belly, Katahdin, and Dorper) and produces wool for artisanal use with Creole and Chiapas sheep, in



**Figure 3.** Sheep wool per Rural Development District (average production from 2019-2020). Based on data from Servicio de Información Agroalimentaria y Pesquera, Secretaría de Agricultura, Ganadería y Desarrollo Rural, México (2023). The figure is the original work of the authors.



**Figure 4.** Sheep under a grazing system with overnight confinement (Atitalaquia, Hidalgo). The picture is the original work of the authors.



**Figure 5.** Intensive sheep production in confinement with roofed pens and slatted flooring (Yebucivi, Almoloya de Juarez, Estado de México) The picture is the original work of the authors.

Oaxaca and Chiapas. The north zone is dedicated to meat production; however, it was the main wool supplier for decades, the reason why a large population of Rambouillet animals is still maintained (Bobadilla-Soto *et al.*, 2015). An important number of sheep in the country is the so-called genetically ‘criollos’ or ‘crossbreeds’, without breed definition, these animals are distributed in all the country and are characterized by their high heterogeneity in body conformation and production (Hernández-Marín *et al.*, 2017).

In Mexico, the largest sheep population is concentrated in four central states namely Mexico, Hidalgo, Puebla, and Tlaxcala) which approximately contributes to 43% of the national sheep inventory. In these regions, the production systems are stratified in the phases of breeding and finishing at pen, with low adoption of new technologies for sheep farming (Bobadilla-Soto *et al.*, 2015). Generally, animals are raised under extensive production systems grazing natural pastures where investment is low with family labor, which results in low

production costs (Chay-Canul *et al.*, 2016; Hernández-Marín *et al.*, 2017).

The National Institute of Statistics and Geography of Mexico (INEGI, 2019) in their national agricultural survey reported social data and mentioned that almost 46% are people with more than 60 years old. Other topics were employment where 25% is a nonpaid workforce, and almost 98% are small farmers (family producers), in which the output of their labor is known to be their main household income. These two situations come with the following important considerations: first, people in the countryside are getting old and not being replaced with younger farmers that could merge the traditional agricultural techniques with new technologies that potentially improve animal production; and secondly, in Mexico, there is a powerful perspective of what the family labor means to the national production. In this regard, the period of 2019-2028 has been declared the decade for family farming by the Food and Agriculture Organization of the United Nations, recognizing the important role that family farming has for food security (#ZeroHunger world from the Sustainable Development Goals-UN) and climate change mitigation (#ClimateMitigation from the Sustainable Development Goals-UN (FAO, 2021). In this sense, family production units are efficient and sustainable from a peasant perspective, but not from the industrial one. Therefore, more governmental attention and multidisciplinary academic research are required on these family productive systems in Mexico, to develop adequate programs for the acquisition of infrastructure and innovation, access to markets and information, and generate adequate policies for investments in sheep production.

It has been estimated that around 50,000 producers are dedicated to sheep breeding, although only 17,000 (34%) of them live totally from sheep production, while approximately 120,000 artisans work the wool which reveals the socioeconomic importance of these animals (Bobadilla-Soto *et al.*, 2015). The current orientation of the Mexican sheep sector is mainly for meat production, where wool production is scarce and, in many cases, represents losses, due to its low price, and wool is mainly used for handicraft purposes (Bobadilla-Soto *et al.*, 2015).

The main product for the meat market is lambs of 20 kg of live body weight at weaning that is brought to a slaughter weight between 35 to 40 kg, which takes the average producer over a year to achieve these weights due to under nutrition (Rubio *et al.*, 2004; Hernández-Marín *et al.*, 2017). However, the lack of competitive value is one of the main issues associated with the lamb market. Therefore, most of the produced lambs are sold to feedlots near Mexico City (the largest market with 25

million inhabitants), where they are fed either on high cereal diets or sometimes fed on industrial by-products such as bread waste, molasses, and chicken manure, to achieve favorable live weight gains (250 g/day) (Hernández-Marín *et al.*, 2017; Bobadilla-Soto *et al.*, 2015). Ninety-five percent of sheep meat is consumed in homemade dishes such as *Barbacoa* and *Mixiotes*, and the rest is used for prime cuts (Mondragón-Ancelmo *et al.*, 2020). Mexico City, the State of Mexico, Hidalgo, Puebla, and Tlaxcala are the states with the highest demand for this product (Bobadilla-Soto *et al.*, 2015).

In Mexico, the annual per capita consumption of sheep meat (1.0 kg) is lower compared to chicken meat (21.8 kg), beef (16.5 kg), and pork (15.1 kg) (Hernández-Marín *et al.*, 2017) being the year 2019, the highest value recorded where the Mexican meat council reported a per capita consumption of chicken, pork, beef, and sheep meat of 19.6 kg, 15.3 kg, 33.7 kg, and 0.6 kg, respectively (Hernández-Marín *et al.*, 2017). The last official published data in 2009 mentioned that the potential consumption of sheep meat would have been half a kilo per person (Mondragón-Ancelmo *et al.*, 2014), being 50% less than that reported in 2001 (Hernández-Marín *et al.*, 2017; Mondragón-Ancelmo *et al.*, 2014). The average price per kilogram of live sheep in 2019 was 42.99 Mexican peso (USD 2.28), and the national meat reached 90.89 Mexican peso (4.82 USD), being Mexico City and the metropolitan area the best-paid region at 99.51 Mexican peso (5.0 USD) (Mondragón-Ancelmo *et al.*, 2012).

Sheep production has possibilities of development, with competitive prices for the producer and for the trader, with the option of diversifying the offer of value-added products (*Barbacoa*, *Pancita*, *Consomé*, and cuts) in markets and restaurants (Hernández-Marín *et al.*, 2017; Bobadilla-Soto *et al.*, 2015). However, the development of sheep production has been affected by the productive deficiency of flocks. For example, in 2006 there was a population of 6.4 million heads, of which 2.1 million were slaughtered, that is 32.8% of the population when in other countries more than 50% of their flocks are slaughtered (Mondragón-Ancelmo *et al.*, 2014).

Considering the results of the National Agricultural Survey of the National Institute of Statistics and Geography (INEGI, 2019), the 5 main problems expressed by producers are high costs of inputs and services, difficulties in marketing, difficulties in exporting, lack of training and technical assistance and loss of soil fertility. Thanks to this type of diagnosis, some strategies can be used to promote the consolidation of cooperatives, where farmers can be advised to interdisciplinary groups to improve animal production, the transformation of final products, and their sale. These multidisciplinary groups must have technical

capacities to carry out advice from agronomists, animal scientists, veterinarians, technicians, and marketing professionals for improving commercialization. An example of this is 'La cooperativa Chiapaneca' (Producers-La Chiapaneca, 2022), a collaboration of small coffee producers and associations that promote fair trade, which currently has distribution in different points of sale in five European countries.

The evident need for organization between producers, marketers, industry, researchers, academics, and public sector agencies related to the sheep production chain, have resulted in the development of the Mexican Standard NMX-FF-106-SCFI- 2006 (Livestock products - sheep carcass - classification). The purpose of this regulation is to guide and strengthen the chain of production, transformation, commercialization, and consumption of sheep meat, through the definition of the quality characteristics that the carcasses must meet for their commercialization, so they can enter competitive national and international markets. This also serves as a guide for the organization of cooperatives that, together with technical advice, achieve common objectives to favor the income of small producers.

#### **The special case of Pelibuey sheep (hair sheep breed)**

Globally, hair sheep breeds are not well known and in Mexico rearing Pelibuey sheep is very common, especially in regions where there is high temperature and humidity. Therefore, in this section, we decided to provide some details on Pelibuey rearing.

The tropical region in Mexico accounts for over 28 % of the national territory, and the sheep industry in this region contributes to 25 % of the total sheep meat

production. Tropical sheep production is performed under marginal environmental conditions characterized by low inputs and low technology adoption focused on hair sheep (primarily the Pelibuey breed) (Morales-Martínez *et al.*, 2020; Magaña-Monforte *et al.*, 2013; Ruiz Ramos *et al.*, 2016; Chay-Canul *et al.*, 2016) (Figure 6). Mature ewes are grazed on pasture with minimal or no feed supplementation, which commonly results in seasonal fluctuations in energy intake and use of body reserves resulting in low meat production (Ruiz Ramos *et al.*, 2016, Chay-Canul *et al.*, 2016). In Mexico, hair sheep breeds are used for meat production and are important for the local economy of the Mexican tropics (González-Garduño *et al.*, 2011; Ruiz Ramos *et al.*, 2023; Aguilar Hernandez *et al.*, 2016; Rivera-Alegria *et al.*, 2022).

#### **Present and future of the new adapted and selected breeds: the case of the "Mexican Pelifolk" breed**

In 2021, in the region of Zapotlanejo, Jalisco, thanks to genetic improvement done by crossing Black Belly and Pelibuey females with Suffolk males, it was possible to certify by the Secretary of Agriculture the pure Mexican breed called Pelifolk. This breed has a very good adaptation to different climates and production systems due to its rusticity and type of coat, and improved meat yield. At the time of the breed certification, around 90 producers in Jalisco accounted for 4,500 animals, also adding the distribution in other states that continues to increase. The producers of the Association have the conditions for breed exportation, which is an example that good organization among the union generates excellent results to improve the conditions of sheep production in Mexico (SADER, 2022).



**Figure 6.** Pelibuey sheep in tropical Southeast Mexico (Tabasco). The picture is the original work of the authors.

## Health

This subsection discusses main bacteria-related problems to Mexican sheep. However, we chose to discuss the main health problems associated with economic losses.

Prevention of diseases, regardless of the production objective, must be done considering production aspects not only linked to animal welfare but also to labor welfare. This will allow the optimization of labor and production and will lower costs for treatments or for eliminating unproductive or sick animals. Carrying out correct practices in animal production has the final goal of producing healthy and safe food, by enabling self-control mechanisms to minimize health risks (Calderón-Cabrera *et al.*, 2022). However, most sheep production systems in Mexico are under extensive conditions, and the main challenges are the prevention of diseases such as brucellosis, mastitis, and paratuberculosis (Calderón-Cabrera *et al.*, 2022; Méndez-Lozano *et al.*, 2015; Carrera-Chávez *et al.*, 2013).

Epididymitis from *Brucella ovis* infection is one of the important diseases in the Mexican sheep farming (Méndez-Lozano *et al.*, 2015). This infection mainly affects males and causes decreased fertility, epididymitis, chronic testicular atrophy, and sterility. Females rarely are infected; however, this disease may also cause mortality in females (Méndez-Lozano *et al.*, 2015; Carrera-Chávez. *et al.*, 2013). Commonly, the sexual contact is the main route of infection; however, the venereal passive transmission during the breeding season is possible since the females may be carriers for 2 months. The combs tests, ELISA, and double immune diffusion are frequently used for the serological diagnosis of *Brucella ovis*, the latter is currently the most prevalent in Mexico with a 92 % sensitivity and 100 % specificity (Méndez-Lozano *et al.*, 2015). In Mexico, a national program to eradicate this disease began in the 1990s, and at least since 2002, all males with more than 8 months of age must be sampled. Since 1974 (when the first subject of *Brucella ovis* reported in Mexico), studies have been performed in different regions of Mexico with the purpose to examine the prevalence of *Brucella ovis*. There are even reports that *Brucella ovis* in Mexico was exterminated in 1991 (Carrera-Chávez *et al.*, 2013). However, others reported an overall prevalence of 2.4 % in several states of Mexico (including Puebla, Veracruz, Hidalgo, Jalisco, Tlaxcala, Guanajuato, and Nuevo León) with 20.5 % of positive flocks. For the control of *Brucella ovis*, it is important that all rams used for breeding are diagnostically negative and come from disease-free flocks (Carrera-Chávez. *et al.*, 2013; Méndez-Lozano *et al.*, 2015).

Globally, *Campylobacter spp.* is one of the main causes of ovine abortion. *Campylobacter* abortion in sheep has been primarily associated with *C. fetus* subsp. *fetus* and to a less important extent with *Campylobacter jejuni*. However, since the 1980s, a striking shift in the etiology of *Campylobacter* abortions has occurred (Yaeger *et al.*, 2021). Ovine chlamydiosis is an infectious disease caused by an intracellular gram-negative bacterium (Palomares Reséndiz *et al.*, 2020). Abortions are critical for sheep production since they are associated with the lack of lamb and milk production which led to major economic losses. In humans, *C. abortus* causes conjunctivitis, pneumonia, and abortion (Guerra-Infante *et al.*, 2022) therefore its prevention is of high importance. In Mexico, there are no comprehensive epidemiological studies on sheep populations, however, according to the Office International des Epizooties (OIE), the widespread *Chlamydia spp.* in ovine causes great damages to sheep breeding nationwide (Palomares Reséndiz *et al.*, 2020; Jiménez-Estrada *et al.*, 2008). In addition, the informal trade of animals between producers promotes contact of sheep with other infected animals while, imported sheep in Mexico comes from Australia and New Zealand, which are free of *C. abortus*, however, imported animals are not tested before their arrival and can be in contact with native sheep. In this sense, some imported ewes had late-abortions during quarantine periods as well as miscarriage shortly after being introduced into the flocks (Guerra-Infante *et al.*, 2022; Manuel Jiménez-Estrada *et al.*, 2008; Palomares Reséndiz *et al.*, 2020).

Leptospirosis is zoonotic and this bacterium is transmitted through direct or indirect contact with urine of infected animals (Gabriel-Véjar *et al.*, 2022), however, its diagnosis is relatively difficult since the clinical signs are limited. In Mexico, normally, sheep could be in contact with the serovars Hardjo and Tarassovi, which are frequently found in cattle (Gabriel-Véjar *et al.*, 2022).

Mastitis compromise productive efficiency and animal welfare in sheep farming (Mørk *et al.*, 2007). Cases of subclinical and clinical mastitis in sheep are frequently related to *Staphylococcus aureus* considered the most clinically important in sheep herds and the prevalence of *Staphylococcus coagulase negative* (SCN) has been linked to high somatic cell counts in dairy sheep (Velázquez-Ordoñez, 2015). From the economic perspective, mastitis control is challenging, however, the economic losses can be minimized by effective management and control programs. In Mexico as in other parts of the world, mastitis diagnosis in sheep is very rare and this health problem deserves further attention (Ruiz-Romero and Vargas-Bello-Pérez, 2023).

## Welfare

Welfare is a very broad concept but, in this review, welfare will be seen as an inherent trait in the production system. Therefore, this subsection will integrate animal welfare into the Mexican sheep production system and will provide some thoughts on how to improve it in the mid- to long- terms.

Like in other farmed animals, sheep welfare has become a primary concern for both the sheep industry and the public (Morris, 2017; Sevi *et al.*, 2009). Farmers, scientists, veterinarians, policymakers, and animal advocates are responsible for understanding the advances and benefits of the application of sheep welfare for improving their health and production. Improving animal welfare has been and will be a key factor in social acceptance of livestock operations, especially in relatively wealthy societies (Rutter, 2017). Additionally, nowadays a greater proportion of consumers are likely to make their purchases based on their awareness on how farming systems are ‘welfare friendly’ (Paraskevopoulou *et al.*, 2020). It is well established (Morris, 2017; Rutter, 2019; Paraskevopoulou *et al.*, 2020) that in some consumer segments, extrinsic factors (e.g., product origin, animal welfare, farming practices, social and religious values, climate change, and environmental issues) appears to be an essential factor for purchase decision (Vargas-Bello-Perez *et al.*, 2022). Hence, information on animal feeding and management, environmental factors, and animal welfare are very important for many consumers (Paraskevopoulou *et al.*, 2020). Moreover, this information increase consumer willingness to pay (Morris, 2017; Rutter, 2019), however, ethical values are hardly transmitted to consumers (Rutter, 2019), and in this regard, Mexican consumers are moving toward the same direction (Alanís *et al.*, 2022; Miranda-de la Lama *et al.*, 2017).

Improving sheep farming practices and welfare can benefit animals and humans and, one of the challenges, even for intensive sheep systems, is to provide environmental enrichment or housing enhancement that leads to stimulating natural behaviors. Conversely, extensive production systems are similar to those with wild environmental conditions but face difficulties for technical and veterinary assistance and selling of products in large markets (Rutter, 2019; Miranda-de la Lama *et al.*, 2017).

In Mexico, sheep in extensive production systems are free to move within a habitat that ensures physiological and behavioral functions (Miranda-de la Lama *et al.*, 2017). However, climatic changes generate different temperatures and variety in the availability of resources. In extensive systems, sheep are directly exposed to these

circumstances which can affect feed intake, production performance, and reproductive efficiency as well as negative effects on health (Soumya *et al.*, 2022). Management strategies such as well-ventilated barn facilities, avoiding working with animals during the hottest times of the day, use of sunshades, and use of water spray systems with fans would help animals to cope with hot seasons (Theusme *et al.*, 2021).

However, grazing can also have adverse effects on animal welfare, through seasonal variations in herbage quantity and quality; thus, grazing animals are typically under nutritional stress (Morris, 2017). In this regard, sheep can use relatively low-quality forages and are commonly raised in housing systems with little supplementation. For sheep, it seems that improving pastures nutritional quality along with restricted grain supplementation not only supports production and quality of final products but also improve animal welfare. Another problem that compromises sheep welfare are gastrointestinal nematode parasites that also negatively affect sheep production in Mexico. However, this review just focused on bacteria-related problems and parasitic diseases will not be covered.

Under in-housing conditions, seek enriched environments that favor the display of natural behaviors and improve productivity (Aguayo-Ulloa *et al.*, 2014). The use of bedding material in pens, such as straw, is a useful method to enrich the environments of the lambs (Teixeira *et al.*, 2015). Bedding material reduces soil moisture and acts as a heat-insulating material to prevent hypothermia, improving lambs’ welfare (Teixeira *et al.*, 2015; Mellor and Stafford, 2004).

In sheep, there has been a trend for modulating maternal nutrition for fetal programming (Tajonar *et al.*, 2023). However, most sheep production in Mexico are on small-scale farms, where pregnant ewes often experience under nutrition in extensive systems that could adversely affect the offspring development and productive performance. In addition, during critical times, such as births, there must be a routine of constant supervision by staff, to reduce the percentage of mortality at birth, ensuring that newborn lambs drink colostrum during the first hours of life and ensuring a dry environment to avoid hypothermia (Mellor and Stafford, 2004).

The Mexican sheep sector needs to improve welfare assessment methods and be transparent about how sheep are produced to meet consumer expectations. In this regard, a framework for the description and measurement of animal welfare indicators in sheep farming should be provided, allowing for the reporting, monitoring, and benchmarking of sheep in Mexico, especially in extensive systems. For that, it is important

to consider the "3'S principle" (Aguayo-Ulloa *et al.*, 2014) which suggests improving animal experiences and avoiding animal pain when carrying out husbandry practices, such as tail docking or castration. Since tail docking is an invasive and painful procedure, it must be carried out seeking a multimodal treatment, with the use of analgesics and medications that generate blockade of pain neurotransmitters, performing the technique in the first week of the lamb's life (Orihuela and Ungerfeld, 2019) and, when appropriate, perform a genetic selection that does not require this procedure (Scobie and O'Connell, 2002). As well as constant training of personnel, considering skills to identify signs of pain or illness.

The concept of animal welfare contemplates the entire life cycle of the animal, which includes transport and its death. To preserve animal welfare and quality of the products, in Mexico, there are two mandatory standards for these important events: The Official Mexican Standards NOM-051-ZOO-1995, humane treatment in the transport of animals (SENASICA, 2022a) and NOM-033-SAG/ZOO-2014 Methods to kill domestic and wild animals (SENASICA, 2022b). Also, training and advice from technicians and veterinarians to producers and personnel should encourage and promote the benefits of carrying out these standards, to improve quality and value-added and facilitate the marketing of products for national consumption and exportation.

According to the 2019 Mexican National Agricultural Survey (INEGI, 2019), basic husbandry practices, such as livestock identification, vaccination, deworming, and preparation of balanced diets, are still necessary from 25 to 65% of livestock production units, which can be very close to the reality of sheep producers. Therefore, the adoption of technologies in either extensive or intensive sheep production systems depends on the diagnosis of the needs and level of technology from each one.

Today, there is a trend for Precision Livestock Farming (PLF) concerning recruited available technologies for improving production in the sheep sector (Vaintrub *et al.*, 2021). For example, in Europe, the Small Ruminant Technologies Platform (2021) and the H2020 Tech Care project (2021) are research programs that share knowledge aiming to improve production efficiency, where all players in the production chain, including researchers, advisors, and farmers, participate to improve awareness of existing technologies. There are various PLF solutions tailored to large-scale sheep farming and other technologies are constantly evolving. Reduced labor- and feed-related costs as well as enhanced productivity of animals are the main goals of these technologies (Vaintrub *et al.*, 2021). However, extensive sheep production that is partly affected by government policies and internal cultural dynamics as

well as local and global markets does not always encourage the application of novel technologies (Morris, 2017). The economic stability of farmers, the reliance on new technologies, and the openness of farmers to new ideas seem to be the main factors limiting the broad use of innovative products (Vaintrub *et al.*, 2021). Mexico needs to adopt and promote the use of technologies that could help to perform diagnoses and enhance animal health as done in South American countries such as Argentina.

## CHALLENGES AND OPPORTUNITIES TO ACHIEVE PRODUCTION SUSTAINABILITY

Consolidation of the Mexican sheep sector, rising costs of feed and energy, ongoing losses from predators, and declining consumption, in combination with competition from imports of lamb cuts, have taken their toll on Mexican producers. Nowadays, production sustainability is needed and, in this case, since 2015, The United Nations (UN) had been working forward for better conditions for the world through several actions categorized in the 17 Sustainable Development Goals (SDG). The UN member countries are working on multiple approaches that enhance health and education, reduce inequalities, and boost economic development, while tackling climate change (UN, 2022). These goals apply to any animal production system and must be used as guidelines for considerations related to sheep production. The following section discusses some other challenges and opportunities that the authors see as key for the development of Mexican sheep sector.

### Climate change

Climate change is the alteration of ecosystems that threaten the safety of present and future generations (Marino *et al.*, 2016; Sejian *et al.*, 2017), and sheep farming is also vulnerable to its negative consequences (Montossi *et al.*, 2013). Global warming affects Mexican sheep sector in different ways including (a) impacts on the availability of pastures; (b) impacts on the quantity and quality of pastures and forage crops; (c) impacts on the circulation of pests and diseases; and (d) impacts on weather and extreme events with direct consequences on health, growth, and reproduction. Native sheep breeds in Mexico are more adaptable to harsh environmental conditions than exotic breeds. Consequently, crossbreeding is effective to sustain production and tackle climatic change (Mondragón-Ancelmo *et al.*, 2014).

Briefly, mitigation strategies for climate change on the sheep sector in Mexico can be categorized as those: (a) related to nutrition, supplementation, and feeding management; (b) to rumen fermentation control and modifiers; (c) to animal breeding and intensiveness of

production. The first two options involve strategies that directly or indirectly affect ruminal fermentation. Yet not all these options are practical due to the high costs or inconsistent effectiveness. In addition, Mexican sheep production should consider reducing the carbon cost and footprint of sheep products through efficient breeding programs (Mondragón-Ancelmo *et al.*, 2012; Montossi *et al.*, 2013; Sejian *et al.*, 2017).

### Natural resources

Mexican sheep farmers are mainly performed under extensive production systems, which primarily use pastures located in marginal areas (Hernández-Marín *et al.*, 2017). From the consumer side, there is also an increasing trend toward sheep products raised naturally (Morris, 2017). Therefore, in Mexico, the sheep industry could be easily adapted to satisfy this trend. Widespread natural pastures and diverse plants with bioactive plant secondary metabolites (PSM) are promising prospects in Mexican sheep production. Hence, efforts should be made to reduce the use of drugs, mainly for health and reproductive management, by replacing them with natural PSM. These strategies include the use of plants to reduce intestinal parasitic loads (Hernández-Marín *et al.*, 2017), or a diet using pre- and/or pro-biotics to stimulate immune system, or the manipulation of inter-individual relationships to trigger reproductive activity. This is an area where innovations can be developed through close links between researchers and farmers. Additionally, labeling information about production systems (i.e., animal friendly and/or environmentally friendly) is important for consumers concerned about the safety of lamb meat, animal health and sensory characteristics of meat (Silva *et al.*, 2022).

### Species loss

In Mexico, like in other tropical developing countries, herds of crossbred or upgraded goats from imported germplasm during the second half of the past century are becoming common. Reproductive programs in the extensive sheep systems in Mexico are practically nonexistent. There is a lack of technical assistance and information, such as recording systems, and technical support by the government and universities still make the development of these programs difficult (Campos *et al.*, 2020). The indigenous sheep genetic resources of Mexico have high within-breed genetic variations (Campos *et al.*, 2020; Robles-Jimenez *et al.*, 2022). Though, there has been not enough efforts to enhance genetic merits of the native sheep. The lack of sheep breeding programs leads to scarce availability of elite nucleus flocks and there are no distribution schemes for the improved genotypes (Campos *et al.*, 2020; Mondragón-Ancelmo, *et al.*, 2014). Therefore, these

genetic programs have not been successful in improving sheep productivity (Robles-Jimenez *et al.*, 2022; de Azambuja Ribeiro and González-García, 2016). Developing genetic selection of sheep to match productive traits as well as their ability to cope with the specific environmental conditions of Mexico is vital to ensure adaptability.

### Sustainable sheep production and consumer preference trends

Globally, improving sustainability is the core of debates on the future of agriculture (Morris, 2017; Paraskevopoulou *et al.*, 2020). The need for sustaining agricultural production and the livelihoods of producers, restoration of production potential, efficient use of limited resources and reduction in production of harmful by-products, demands the development of management practices that make food production systems more efficient, not only in terms of producing more food per unit of limited resource (e.g. water) but also in terms of producing more food per unit of input and harmful byproduct produced (e.g. methane) (Morris, 2017). In this regard, Mexican sheep farming plays important social, cultural, economic, and environmental roles, however, this sector faces multiple challenges at local scales (Mondragón-Ancelmo *et al.*, 2020). Besides, the impacts of climate change are being manifested through increased surface temperatures, drought, and changing precipitation thereby affecting global animal agriculture productivity, especially in arid and semi-arid regions of the world like Mexico (Díaz Solís *et al.*, 2016; Hernández-Marín *et al.*, 2017). In this sense, sheep production systems in Mexico should be adapted to local weather patterns and variability. So, alternative management strategies for dealing with drought might include increasing or decreasing stocking rates based on the current condition of the pasture, season of the year, and the direction and rate of change in animal body condition. However, these reactive strategies have market problems because the producers need to sell when many other producers are liquidating animals and prices are low, and they then must restock when prices are very high after the drought (Díaz Solís *et al.*, 2016). Water-related problems are comparatively irrelevant in low-input systems in this country based on grazing and utilization of local natural resources (Díaz Solís *et al.*, 2016). While multiple approaches are proposed to help mitigate the effects of climate change on sheep production, those that offer the largest potential climate and sustainability benefits, while avoiding negative tradeoffs, should be the focus. This could mean different approaches (and levels of focus) for the production side (pre-market) versus demand side (the market and beyond). Overall, special attention should be paid to applied and innovative research to adapt the sheep sector to future climate and environmental changes and a

balance between production to meet increased demand for animal proteins and environmental management must be met.

In Mexico, the sustainability of extensive systems for sheep will depend on enhancing their productivity and proficiency in the terms of meat, milk, and fiber production (Mondragón-Ancelmo *et al.*, 2020; Robles-Jimenez *et al.*, 2022). However, extensive sheep systems face numerous challenges including keeping environment, natural resources, and animal welfare (Paraskevopoulou *et al.*, 2020). Almost all sheep production in Mexico is associated with low-quality pastures, harsh weather conditions, very rudimentary fencing, and limited use of equipment for sheep management (Mondragón-Ancelmo *et al.*, 2020). Under these circumstances, various constraints and limitations are likely to occur and affect animal welfare, animal health and food safety.

### CONCLUSION AND FINAL REMARKS

Sheep farming is undertaken in different ways around the world, providing a variety of products under distinctive ecological and socio-economic circumstances. The sheep sector has a great socio-economic impact in Mexico. However, the development of the sheep sector is relatively slow since it is affected by complex factors such as those related to social, political, and economic changes that impact the population, production, and consumption of sheep, as well as the diversification of production systems throughout the country.

One of the main challenges with sheep production is on extensive systems as they are associated to malnutrition, insufficient care during pregnancy, and lamb mortality. Additionally, animal health and veterinary services are poorly provided and inadequately organized. Another concern for sheep farmers is the overgrazing of pastures and the grazing of immature forest areas. Improvement opportunities in the Mexico sheep sector should consider that: 1) Farms should implement biosecurity measures as the first barrier to keep healthy and productive flocks, 2) Producers have used traditional systems that must be supported by technical advice and technology according to their specific needs, 3) Continuous training for staff in welfare and sustainability topics, 4) Young people need to be aware that the primary sector is the productive root of the planet and a priority to take actions for a sustainable world. They know how to use technology, and could use it for sheep production, 5) The collective work of producers through cooperatives helps to visualize the diversity of products, in addition to contemplating marketing strategies using social networks, and 6) Close communication and cooperation among producers,

academic institutions, and government authorities. Strategies for improving the Mexican sheep production must focus on providing knowledge and training to farmers with the support of private and public institutions. In this regard, integrated efforts should be made to enhance sheep productivity in Mexico. The major aspects to be improved relate to feeding management, farmer's training, breeding management, and marketing approaches. The training of extension technicians who will, in turn, train communal sheep farmers will go a long way in realizing and exploiting the potential of sheep production. Regarding marketing approaches, the creation of small farmer groups and associations as the potential to increase access to information, increase participation in formal markets and lower transaction costs. Identifying and establishing new market niches could also help improve sheep farming communities to generate greater incomes. However, to shift sheep and goat production from subsistence to a more commercial outlook, it is important to understand aspects of market and marketing. Farmers need to be aware of the preferred characteristics of animals as well as price patterns so that they can plan breeding and fattening programs consistent with the market demand and consumers' preferences. There is also a need for well-organized groups of farmers to improve marketing and commercialization of sheep products. This task should be done with the participation of farmers, veterinarians, and technical professionals. This will improve farmer welfare and ensure the continuity of farmer-family businesses. Moreover, geopolitically, Mexico has trade agreements with Canada and the United States of America; therefore, these contracts should be used to enhance the marketing of sheep products.

Overall, the authors have some suggestions that would further improve the sector to achieve a sustainable sheep industry. For that, Table 1 and Figure 7 summarize the different pillars and variables to be considered for the productive efficiency of Mexican sheep production.

To improve the productive efficiency of Mexican sheep farming systems, players involved in the production chain, governmental authorities, and academic and research institutions, need to work together to understand and integrate three main elements and their complexities, which in turn are related to each other: animal, social, and production systems. We currently live in an interconnected world, in which the decisions made in any situation immediately affect those around it. Therefore, we must continue to remember the concept of one welfare, as the conjunction for decision-making in the production units, and improve world welfare. The sheep as the central element of this article refers to the main objective of the work. In this case, the sustainability of the production system and animal

welfare should be taken as foundations for the improvement of production. Thus, husbandry practices must be based on the principles of animal welfare to achieve animal health and productivity.

The complexity of the Mexican social elements involves a great diversity of conditions that must be preserved

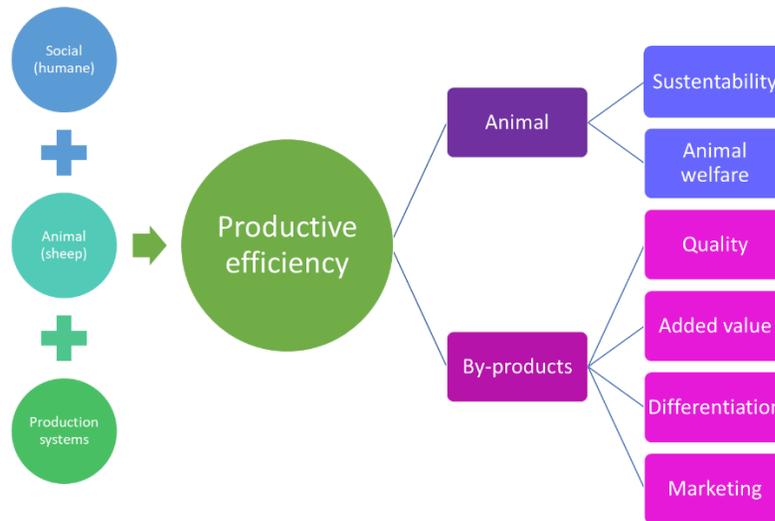
and favored. The production systems together with the variety of weather conditions in the Mexican territory influence animal adaptability to many circumstances. Working to improve the conditions of each sheep production unit in Mexico must be observed and diagnosed from different angles to identify the strengths and weaknesses.

**Table 1. Main guidelines and strategic priorities for improving the productive efficiency of sheep production systems in Mexico.**

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<i>Social (Humane)</i>	
<ul style="list-style-type: none"> <li>• Promote the coordination and continuity of government programs to strengthen sheep production by province or state, through the consolidation of multidisciplinary groups to provide advice and technical support.</li> <li>• Consolidate cooperatives among small-scale producers, advised by multidisciplinary groups, for advice and technical support in animal care and production, seeking conditions that favor improving the quality and diversification of products.</li> <li>• Organized and advised cooperatives must aim to avoid intermediaries that producers carry out the transformation of by-products and their marketing, for sale and distribution in different establishments and through social networks.</li> <li>• Programs for the preservation and dissemination of the cultural value of ethnic groups, their traditions, and crafts (i.e., Tzotzil community and the production of Chiapas sheep wool).</li> <li>• Increase the quality of sheep products including meat, wool, and dairy.</li> <li>• Labeling information about production systems (mainly animal feeding and environmentally friendly production practices)</li> </ul>	<ul style="list-style-type: none"> <li>• and favored. The production systems together with the variety of weather conditions in the Mexican territory influence animal adaptability to many circumstances. Working to improve the conditions of each sheep production unit in Mexico must be observed and diagnosed from different angles to identify the strengths and weaknesses.</li> </ul>
<i>Animal (Sheep)</i>	
<ul style="list-style-type: none"> <li>• Achieve the understanding that animal welfare is the foundation for efficient production.</li> <li>• Preserve and favor the selection of breeds adapted to the ecological niches of the national territory (i.e., Chiapas, Pelibuey, Pelifolk).</li> <li>• Implement bio-stimulation techniques for breeding improvement (i.e., male effect, female effect, photoperiod management) to reduce costs and increase reproductive outputs.</li> <li>• Perform productive management free of pain and stress.</li> <li>• Promote transport and slaughter conditions by regulations and standards.</li> <li>• Take advantage of the use of industrial by-products, as non-competitive food input alternatives for human or monogastrics consumption.</li> <li>• Continuous training of personnel involved in the care and management of animals, for improving timely diagnostic techniques.</li> <li>• Select rustic animals with resistance to diseases.</li> <li>• Staff training to increase lamb survival.</li> <li>• Rational use of antibiotics.</li> <li>• Development and use of records of nutritional indicators for frequent animal monitoring to reduce feed wastage, nutritional imbalances, and improve welfare.</li> </ul>	
<i>Production system</i>	
<ul style="list-style-type: none"> <li>• Carry out situational diagnoses in each production unit.</li> <li>• Integrate the strategies of the Sustainable Development Goals of the FAO to promote sheep production.</li> <li>• Identify the needs of each production unit according to the level of intensification to favor the adoption of relevant technologies.</li> <li>• Encourage the development and implementation of national Precision Livestock Farming technologies for automated monitoring of the health and production status of the animals and facilitate tasks for the staff.</li> <li>• In extensive grazing systems, the quality of forages and/or pastures must be considered to supply diets according to the needs of the animals.</li> <li>• Support extensive dairy sheep grazing-based systems through policy and designation of appropriate land uses and make sustainable use of them.</li> <li>• Adaptation of grazing systems to environmental changes (e.g., air temperature, water availability, soil system, vegetable, and animal biodiversity).</li> <li>• Greenhouse gas mitigation.</li> </ul>	

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**Figure 7.** Different variables are to be considered for the productive efficiency of Mexican sheep production.

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### Author contribution statement (CRediT). E. Vargas-Bello-Pérez:

Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing—original draft preparation, Writing—review and editing, Visualization, Supervision. **C.A. López Díaz:** Investigation, Formal analysis, Writing—review and editing. **R.A. Ruiz-Romero:** Investigation, Writing—review and editing. **A.J. Chay-Canul:** Investigation, Writing—review and editing. **H.A. Lee-Rangel:** Investigation, Writing—review and editing. **M. Gonzalez-Ronquillo:** Investigation, Writing—review and editing. **N. Ghavipanje:** Investigation, Methodology, Formal analysis, Data curation, Writing—original draft preparation, Writing—review

and editing. **K. Tajonar:** Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing—original draft preparation, Writing—review and editing, Visualization, Supervision.

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