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The availability of food in Mexico: an approach to measuring food security

Yadihra Cruz-Sánchez[1], Alma Aguilar-Estrada[2], Julio Baca-del Moral[3] and Alejandro Ismael Monterroso-Rivas[4*]

Abstract

Background information Mexico faces a great challenge in producing, storing, and distributing food to guarantee the food security of its population. Natural disasters, climate change and changes in land cover are dynamic drivers affecting food production. In this study, we propose a method for assessing food security by evaluating the amount of food in Mexico that is available to meet the demand of its population. An indicator of food availability based on environmental, social, production and food supply variables is proposed.

Methods Food availability in Mexico's 2471 municipalities was assessed using five sub-indicators covering environmental and social conditions of production, food supply, caloric and protein sufficiency, and food supply. A database of 19 variables was integrated to calculate an index of food availability by municipality. Spatial analysis techniques were used to identify areas with specific needs and to formulate public policy recommendations.

Results The availability of food is not a problem at all in 90% of the municipalities in the country. We found that the environmental and social conditions are suitable for producing food from agriculture and livestock and there are sufficient food outlets. The caloric demand and protein requirements of the population can be met in at least 87% of the municipalities. Thus, the environmental and social conditions are good in more than 85% of the municipalities. If food production and availability are sufficient; then, the problem of food insecurity may be due to other causes.

Conclusions and recommendations The conclusion is that food insecurity in Mexico is influenced by additional factors. An urgent intervention is needed, including public policies to provide economic support to the most affected segments of the population.

Keywords Food production, Food supply, Environmental conditions, Social conditions

Introduction

With less than a decade to go before the deadline for achieving the Sustainable Development Goals (SDGs), the reality is clear: global hunger will persist beyond 2030. New estimates, based on the frequency and intensity of conflicts, extreme climatic conditions and economic slowdowns, point to the urgent need for bold action to accelerate progress [1].

In this global scenario, it is estimated that between 720 and 811 million people worldwide will be hungry in 2020. Using the midpoint of this range (768 million) as a reference, this represents an increase of around 118 million people compared to 2019. The most affected regions remain Africa (21% of countries), Asia (9% of countries) and Latin America and the Caribbean with 9% of total countries affected [1]. The root of the problem lies in the large food systems, the myriad networks that have formed to produce, store, package, process, distribute,

*Correspondence:
Alejandro Ismael Monterroso-Rivas
aimrivas@correo.chapingo.mx
[1] Departamento de Fitotecnia, Universidad Autónoma Chapingo, Km 38.5 Carretera, Mexico-Texcoco, Texcoco 56230, México
[2] Consultor Independiente, Mexico City, México
[3] Centros Regionales Universitarios, Universidad Autónoma Chapingo, Km 38.5 Carretera, Mexico-Texcoco, Texcoco 56230, México
[4] Departamento de Suelos, Universidad Autónoma Chapingo, Km 38.5 Carretera, Mexico-Texcoco, Texcoco 56230, México

market and consume food [1]. Infrastructure plays a critical role in food security. In Ethiopia, smallholder farmers, both men and women, face barriers, such as limited access to agricultural infrastructure and facilities [2].

In line with the complexity of food systems, the inaccessibility of healthy diets emerges as a critical factor linked to the increase in food insecurity and various forms of malnutrition due to the high prices of foods considered healthy. This challenge will become more pronounced by 2020 and will be a greater threat than in previous periods, particularly in developing countries. The increase could be attributed to the responses adopted, in particular the closure of borders in response to the COVID-19 pandemic. It has now improved with trade openness, which plays a crucial role in improving food security, as in the case of 37 countries in Africa [3]. Opening community marketing sites has provided farmers in other countries with a secure outlet for their food production, linking smallholders to markets without conflicting with social and cultural norms [4].

Although [5] addressed food security through the prevalence of undernourishment, this indicator has been shown to fail to capture the complexity and multidimensional nature of food security. This is evident in places where food insecurity is alarming in all four dimensions, as pointed out by Mbunga et al. [6]. Currently, there are significant gaps in the methodologies used by FAO to measure food security and food availability. Although it uses indicators such as calorie adequacy and dietary diversity, it does not consider the dimensions of food utilisation and stability, which limits a comprehensive assessment [7]. Furthermore, the focus on national indicators of undernutrition based on food availability estimates does not adequately address the situation at the household level, given the limited data and knowledge at the household level [8]. In terms of food availability, the FAO focuses on physical access to food, neglecting emerging aspects such as environmental sustainability [9]. Although it assesses the sufficiency of food through production and imports [10], its focus on food balance sheets has limitations in accurately estimating the prevalence of malnutrition [11]. Furthermore, regional measures used to measure food availability neglect the specificities of small scales [12], highlighting the need for a more comprehensive and detailed approach to assess food security at the global level.

Given the limitations of current methodologies, the proposal for measuring food availability in the present work stands out for its comprehensive and detailed approach, taking into account the environmental and social conditions of production, food supply, calorie and protein sufficiency, and food supply at the community level.

In addition, there is a call for a comprehensive analysis of food insecurity that allows for the design of long-term, tailored interventions. It is therefore proposed that food security be addressed through these four dimensions: availability, physical and economic accessibility, use and stability of food in time, using specific indicators. An example of the application of these dimensions is the Economic Commission for Latin America and the Caribbean (CEPAL), document for four Andean countries: Bolivia, Colombia, Ecuador and Peru [13].

In addition, consideration of spatial and temporal changes in land cover (croplands, forests, grasslands and aquatic areas) is critical for assessing food security. These changes can either alleviate or exacerbate the challenge of food production in different environments [14]. In agricultural production areas, climate disruption can challenge crop productivity, affecting the world's ability to sustain adequate food production for a growing population [15]. Ocwa et al. [16] found that a temperature increases of 1 to 4 °C in warm areas led to a decrease in agricultural yields of 5 to 14%. In cold regions the global increase was less than 5%. The decrease in precipitation led to a decrease in yields from 25 to 32%.

In this context, it is crucial to increase crop yields and productivity to address the impact of climate change on the nutritional value of these crops. For example, the adoption of seasonal climate-adapted agronomic practices for wheat systems in the Mediterranean suggests that there are effective agronomic practices that can be adopted by farmers to improve yields and make an effective contribution to food security [17].

In this regard, Mexico is emerging as a country vulnerable to climate change and land use change, which are already affecting food production and consequently the food security of its population. At least 64% of Mexican soils show some degree of degradation, with 12% of the territory affected by water erosion and 9.5% by wind erosion [18]. In addition, there is a public health crisis due to the increase in diet-related diseases, including malnutrition and obesity. The role of food and agriculture is increasingly seen as a strategic sector [19].

Food insecurity in Mexico is mainly due to the lack of resources to acquire quality food, exacerbated by food inflation, widespread unemployment, and low education, leading to severe food insecurity in several states [20, 21]. This situation is intensified by environmental impacts and an inadequate food supply that does not meet health standards [22]. Factors such as climate vulnerability, poverty rates, and the number of nutrition programs are critical to understanding this problem, highlighting the need for a multisectoral approach to policy and governance [23]. Food insecurity in Mexico also stems from various climatic, socioeconomic, and cultural aspects,

particularly affecting indigenous communities with high rates of chronic malnutrition [24]. Although there was a temporary decrease during the COVID-19 pandemic, the persistence of this problem highlights the urgency of addressing these causes in a comprehensive manner to ensure food security in the country [25].

Conceptual framework

Food security is achieved when all people have physical and economic access to sufficient safe and nutritious food to satisfy their nutritional needs and preferences at all times, permitting them to lead an active and healthy life [26], p.2.). Thus, the four dimensions that are necessary to achieve food security and generate sustainable and functional food supply systems are as follows: (1) availability of food; (2) physical and economic access to food; (3) use of food; and (4) stability over time.

In this paper, we propose an approach to measuring food security based on the first dimension proposed by FAO: the availability of food. Variables summarizing the sources of information available at the municipal level for Mexico were obtained from a previous bibliographic review [27]. An *indicator of food availability* is proposed to measure food security in the country based on the definition of FAO [26].

The concept of food availability has been addressed as the provision of sufficient food through production and distribution, which affects communities' access to food of adequate quality, whether from domestic or imported sources [10]. This concept is explored through methods such as ration cards, community coping strategies, soup kitchens, and private provisioning in Jewish ghettos during World War II [28]. In addition, food sharing addresses the availability and distribution of food by reducing waste, redistributing to those in need, and promoting responsible consumption in line with sustainable development values in diverse communities [29]. Food availability and distribution in communities are critical components of the food system because they affect food security. This concept encompasses both the physical availability and accessibility of food within the food value chain [30].

The FAO defines food availability as "The existence of sufficient quantities of food of adequate quality, supplied through the country's production or imports (including food aid)"[31]. In addition, the "food supply" is included as an important part of the dimension and is defined as "the quantity, quality and varieties of food subject to production (productive practices, environmental conditions, cost) and provision (supply, transportation) which in turn is conditioned by geographical location, climatic factors, distances from the production centers, among others" [26, 32]. In this study, the definition provided by FAO [31] was used as a guideline for the formulation of the "food availability indicator"; however, some concepts addressed in the aforementioned studies were also considered.

There have been few studies of food availability in Mexico [33]. At the national level, the availability of food is measured in conjunction with one or more of the other three dimensions. For example, physical access to food was measured considering the index of marginalization of the locality and the supply of food [34]. At the level of ecoregions, the food efficiency index was measured based on the production and consumption of food [33]. At the state level and for Mexico City, the availability of food was studied from the perspective of production [35]. On the household scale in Xochiapulco, Puebla, the variety of food available was measured, including determining how many months the household supplies would last [36]. Consequently, measuring the availability of food is key measuring food security. It allows monitoring the production, supply and quantity of food, as well as the sufficiency of food energy and the quality of diets for a specific population. However, fisheries, aquaculture and forest products also contribute to the availability of food [5].

Therefore, it is necessary to expand the study of food availability with the use of variables that determine it in a broader sense. In addition, the lack of application of these variables at the municipal level is noted in most studies since the most common measurement scales are at the national and state levels. The municipal scale is the smallest administrative unit for budget distribution Mexico, making it possible to identify the particular environmental, social, infrastructure or food production conditions of each municipality. Thus, our objective was to propose an indicator of the availability of food in Mexico at the municipal level through a set of variables to guide decision-makers in the correct application of comprehensive policies that contribute to improving national food conditions.

Methods

Food availability was estimated for 2471 municipalities in Mexico. Five subindicators were defined based on the concept of "food availability" as well as the "food supply" (Table 1), as detailed below:

a. *Environmental conditions for production*: In terms of land potential, crop productivity is considered to be determined by interactions between climate and ecophysiological processes. It includes four variables: (1) water for production (considering whether the municipalities have irrigated agriculture), residual irrigation, temporary irrigation or a combination of these, (2) suitability of the land for agriculture, (3)

Table 1 Weighting of the variables and sources of information used to measure food availability

Variable	Unit	Class	Value	Source
Environmental conditions for production				
Humidity for production	Categorical	Irrigation–residual–temporary	3	[66]
		Irrigation–temporary	2	
		Temporary	1	
		No data/No agriculture	0	
Suitability of the land for agriculture	Dimensionless	High (3.1–4)	3	[67]
		Middle (2.1–3)	2	
		Low (1.1–2)	1	
		No data (1)	0	
Range coefficient	Animal unit/ha	Very Low (5)	5	[68]
		Low (4–5)	4	
		Middle (3–4)	3	
		High (2–3)	2	
		Very High (1–2)	1	
		No data	0	
Exposure to the weather	Dimensionless	Very Low (5)	5	[67]
		Low (4–5)	4	
		Middle (3–4)	3	
		High (2–3)	2	
		Very High (1–2)	1	
		No data	0	
Social conditions of production				
Marginalization Index (GM)	Dimensionless	Very low	5	[69]
		Low	4	
		Medium	3	
		High	2	
		Very high	1	
No litigation for the land	%	Very High (> 75%)	5	[70]
		High (50–75%)	4	
		Middle (25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
		No data	0	
Primary activities	No	4 primary activities	4	[66]
		3 primary activities	3	
		2 primary activities	2	
		1 primary activity	1	
		No data/None	0	
Up with agricultural insurance or credit	%	Very High (> 75%)	5	[70]
		High (50–75%)	4	
		Middle (25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
		No data	0	

Table 1 (continued)

Variable	Unit	Class	Value	Source
Technical training at PU	%	Very High (> 75%)	5	[70]
		High (50–75%)	4	
		Middle (25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
		No data	0	
Organization of PU	%	Very High (> 75%)	5	[70]
		High (50–75%)	4	
		Middle (25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
		No data	0	
Provision of food				
Agricultural production	Ton	Very high	4	[66]
		High	3	
		Medium	2	
		Low	1	
		No data/No production	0	
Livestock production	Ton	Very high	4	[66]
		High	3	
		Medium	2	
		Low	1	
		No data/No production	0	
Fishing and marine products	kg	Very high	4	[71]
		High	3	
		Medium	2	
		Low	1	
		No data/No production	0	
Caloric and protein sufficiency (produced)				
Calorie availability	%	High (80–100%)	3	[66]
		Middle (50–80%)	2	
		Low (0–50%)	1	
		No data/no production	0	
Protein availability	%	High (80–100%)	3	[66]
		Middle (50–80%)	2	
		Low (0–50%)	1	
		No data/no production	0	
Food supply				
Points of sale (economic units)	%	Very High (> 75%)	5	[72]
		High (50–75%)	4	
		Middle 25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
Markets	%	Very High (> 75%)	5	[73]
		High (50–75%)	4	
		Middle 25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	

Table 1 (continued)

Variable	Unit	Class	Value	Source
Tianguis	%	Very High (> 75%)	5	[73]
		High (50–75%)	4	
		Middle 25–50%)	3	
		Low (10–25%)	2	
		Very Low (0–10%)	1	
Inaccessibility	%	Very Low (0–10%)	5	[74]
		Low (10–25%)	4	
		Middle 25–50%)	3	
		High (50–75%)	2	
		Very High (> 75%)	1	

suitability for livestock activities and (4) the degree of exposure to the climate.

b. *Social conditions of production:* It refers to the characteristics of the population and the conditions in which producers operate when producing food. It is composed of six variables: (1) marginalization index (GM), which was taken from CONAPO, (2) lands without litigation regarding land ownership, (3) percentage of production units (PUs) that have insurance or agricultural credit, (4) percentage of PUs that indicated having received technical assistance, (5) percentage of PUs that are part of an organization and (6) the number of primary activities developed in the municipality (only agriculture, livestock and fishing were considered, excluding activities forestry due to lack of information).
c. *Provision of food:* This includes the goods produced or provided by ecosystems such as food, water, fuel, fibers, genetic resources and natural medicines. In this indicator, three variables are integrated: (1) agricultural production, (2) livestock production and (3) fisheries production. The above reflects the annual production volume in tons (agricultural and livestock production) or in kilograms (fishing). It is worth mentioning that only those products that are edible for people were selected; products destined for livestock feed, ornamental plants or some other purpose, such as cotton, were excluded. Likewise, wax and wool were excluded livestock products, and only honey, meat, eggs, milk and live cattle were considered.
d. *Caloric and protein sufficiency*: This is based on the caloric and protein requirements per capita proposed by FAO and WHO [37], linked to the variety and quality of food consumed by the residents. It includes two variables: (1) availability of calories produced and (2) availability of proteins produced in the municipalities. "Composition tables for food and food products" were used [38], from which the total calories and proteins contained in each of the products from production were obtained. The availability of calories (Kcal) and proteins (Prot) in a municipality was obtained by:

$$\text{PopulationKcal} = [((V)/365)/2388) * 100]/\text{PTot} \quad (1)$$

$$\text{PopulationKcal} = [((V)/365)/2388) * 100]/\text{PTot} \quad (2)$$

where *PopulationKcal and PopulationProt* are the percentage of the population of a municipality that would be covered with the production of food from the same municipality in terms of calories and proteins, respectively. *V* is the total annual volume of agricultural, livestock and fishing production (in grams), in turn converted to kcal and protein (converted to kcal and daily available protein); *2,388 and 35* are daily requirements of calories and proteins for an adult, respectively (FAO, [37]); and PTot is the total population of the municipality.

e. *Food supply:* This is determined based on the food trade and the means to access it. The population mostly acquires its food in some trade, large or small. It integrates four variables: 1) percentage of the population supplied by the points of sale in the municipalities (INEGI-DENUE, excluding all establishments dedicated to the sale of products other than food, including alcoholic beverages and cigarettes), defined based on the thresholds established by [39], considering the size of the points of sale: micro (1–10 employees), small (10–50 employees) and medium (51–300 employees) (ranges established by the World Bank), 2) percentage of the population benefited by mar-

kets and supply centers, 3) percentage of the population benefited by "tianguis"—this is a kind of "mobile market" that is semi-permanent on the street and on certain days of the week, according to the uses and customs of each population in the country—and 4) inaccessibility, which is the percentage of the population with low or very low degree of accessibility to paved roads. This last variable shows an aggregate indicator of information on the existence of paved roads, location of the localities, slope of the terrain, type of vegetation, land use, existence of bodies of water, availability of public transport and travel time to the localities with more than 15 thousand inhabitants.

Food availability index

A database was integrated with the 19 variables and the 2471 municipalities that make up the country [40]. A score was obtained for each of the five subindicators (arithmetic sum of its variables) and then added again to obtain the index of food availability by municipality. The results were grouped into five classes (Table 2 Err or ! Reference source not found.). The database was exported to a geographic information system (ArcMap 10.4.1, ESRI) to generate cartography.

Finally, areas with potential for analysis and public policy recommendation were identified based on the spatial behavior of the food availability index obtained. That is, the class of availability in a municipality and the similarity with neighboring municipalities. For this, a spatial autocorrelation analysis was carried out between values of closest neighbors by applying the global Moran index (Moran, [41]). GeoDa software was used [42] to calculate the statistics and the corresponding cartography. The values range between + 1 and -1, where + 1 indicates perfect positive autocorrelation, -1 denotes perfect negative autocorrelation and a value of 0 indicates the presence of completely random patterns in its spatial distribution (Chasco, [43]). To verify the level of significance, the value of 0.05 was used, so that if $p < 0.05$, the null hypothesis was rejected, suggesting that the attribute being analyzed is randomly distributed among the entities of the study area. Thus, if the p value is not statistically significant, the null hypothesis cannot be rejected, and the spatial distribution is likely the result of random processes. In contrast, if p is statistically significant, the null hypothesis is rejected, and there is evidence for the spatial grouping of the values.

Results

The results for each of the five subindicators are shown in Fig. 1 and briefly described below.

Environmental conditions for food production (ECP). It was found that 26% of the municipalities of Mexico (648) observe "very high" environmental conditions to produce food. These municipalities are characterized by having sufficient humidity for agriculture throughout the year (temporary, irrigation or residual irrigation). They have suitable agroclimatic and soil conditions to produce crops or sustain livestock. Their exposure to climatic phenomena is low or very low (Table 3). Some examples are the municipalities of Joquicingo (State of Mexico), Quiroga (Michoacán), Asunción Ixtaltepec (Oaxaca), San Gregorio Atzompa (Oaxaca) and Tenancingo (Tlaxcala). In contrast, San Pedro Garza García (Nuevo León), Puerto Peñasco (Sonora), Nuevo Laredo (Tamaulipas) and Juárez (Chihuahua) present the lowest environmental conditions.

Social conditions for food production (SCP). The results show that 99% of the municipalities have adequate social conditions for food production (Table 4). Municipalities such as Othón P. Blanco (Quintana Roo), Guasave (Sinaloa), Tuxpan (Veracruz) and Mérida (Yucatán) stand out. They are characterized by being municipalities with a very low index of marginalization, a diversity of primary activities (at least three), free of litigation over land, having several organizations that represent them, having access to agricultural insurance and/or credit, and receiving technical training. However, within the low social conditions there are three municipalities of Chiapas (Capitán Luis Ángel Vidal, Honduras de la Sierra and Rincón Chamula San Pedro) with a high degree of marginalization and no primary activities.

Provision of food (PF). Municipalities with a very high food supply are characterized by having a very high production and variety of agricultural, livestock and/or fishing products (Table 5). Outstanding examples are the municipalities of Ahome (Sinaloa), Culiacán (Sinaloa), Ensenada (Low California), Champotón and Cajeme (Sonora), mainly from the north of the country. Those that do not register food production stand out, San Pedro Garza García (Nuevo León), Iztapalapa (Mexico City), El Parral (Chiapas) and Ciudad Madero (Tamaulipas), to mention a few.

Table 2 Values and classes of the food availability indicator

Range	Class	Description:
0	0	No data/no availability of food in the municipality
(0.1 to 5.0)	1	Low availability of food in the municipality
(5.1 to 10.0)	2	Average availability of food in the municipality
(10.1 to 15.0)	3	High availability of food in the municipality
(> 15)	4	Very high availability of food in the municipality

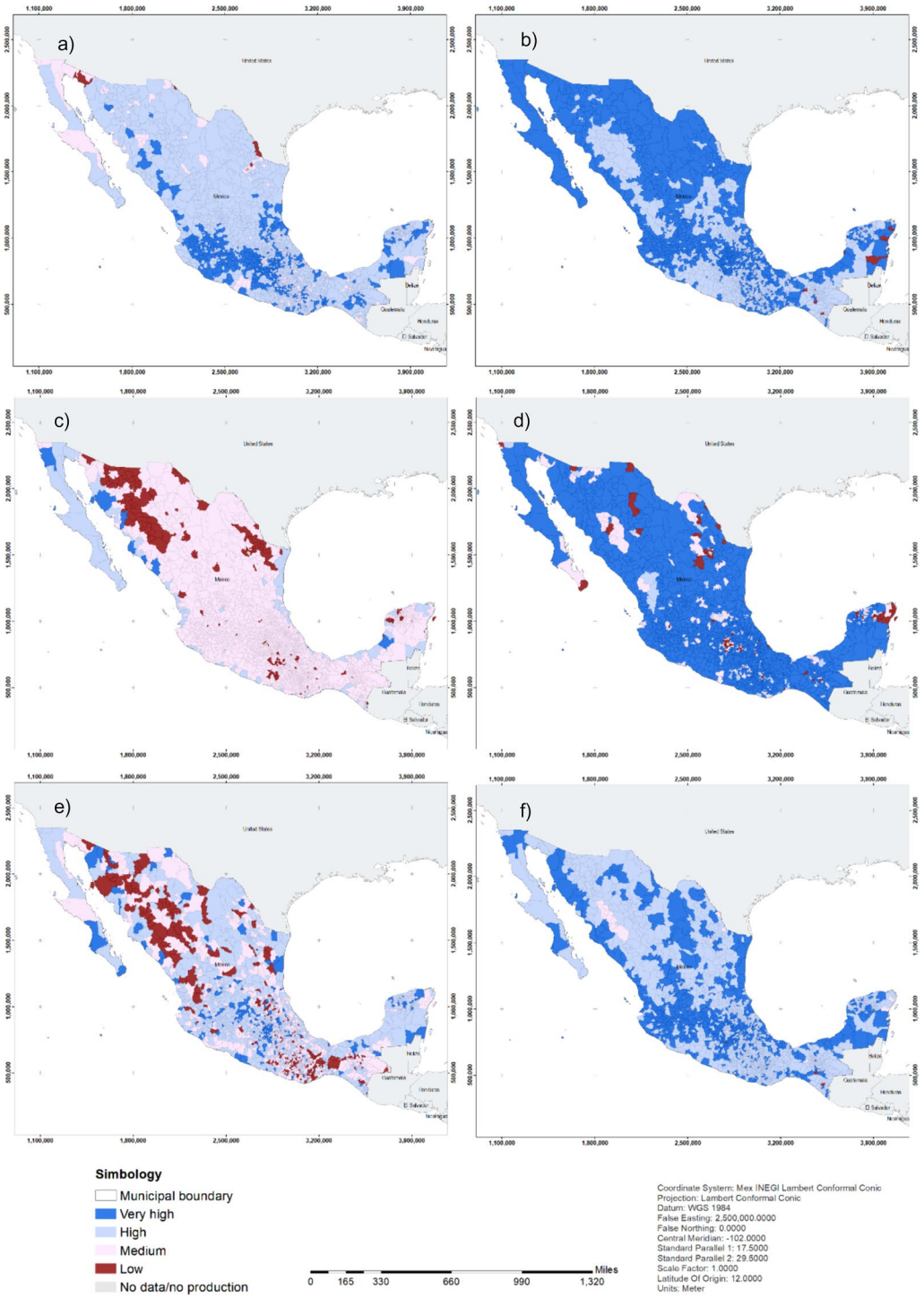

Fig. 1 Spatial distribution at the municipal level of **a** environmental conditions for production, **b** social conditions, **c** food supply, **d** caloric and protein sufficiency, **e** food supply and **f** food availability in the municipalities of Mexico

Caloric and protein sufficiency (CPS). It was found that 80% of the municipalities in Mexico can meet their calorie and protein requirements by having enough of their own food production. Some of them even exceed the requirements of their population by many (Table 6). Therefore, some municipalities that have low food production achieve this category since their population is small (Santiago Sochiapan in Veracruz, Ónavas and San

Javier in Sonora). In contrast, municipalities such as Nuevo Laredo (Tamaulipas) observe little agricultural production but a very large population.

Food supply (FS). Regarding points of sale, markets or tianguis, it was found that more than half of the municipalities observe high to very high coverage. In the case of markets and tianguis, the percentage of population coverage is medium, or they do not reach the entire population. The percentage of inaccessibility is "very low", which is favorable for municipalities since only 6.7% of the population does not have good accessibility (Table 7).

Food availability *indicator* (FA)

By integrating the five dimensions, the food availability indicator was obtained. The contribution of each is shown in Fig. 2. The results indicate that more than two-thirds of the municipalities have a high availability of food. That is, they have high environmental and social conditions for the production of food, so they

Table 3 Environmental conditions in the municipalities of Mexico

Class	Municipalities	%	VARIABLES			
			Humidity	Crop suitability	Pasture	Exposure to weather
Very high environmental conditions	648	26	Irrigation–residual–temporary	High	More than 5 animals/ha	Low and very low
High environmental conditions	1457	59	Irrigation–temporary	Medium to high	More than 5 animals/ha	Medium to low
Average environmental conditions	357	14	Temporary	Medium to high	More than 5 animals/ha	High to very high
Low environmental conditions	9	0.4	Temporary	Low or not suitable	More than 5 animals/ha	No data

Table 4 Distribution of the municipalities of Mexico in social food production category

Class	Municipalities	%	VARIABLES					
			Degree of marginalization	No litigation	Credit and/or insurance	Technical training	Organization	Number of primary activities
Very high social conditions	1120	45	Low	99.6	53.3	94.3	97.3	More than 3
High social conditions	1332	54	Medium	99.7	17.9	93.5	97.4	From 2 to 3
Average social conditions	4	0.2	Medium to High	98.9	0.0	49.7	57.2	2 or less
Low social conditions	15	1	Medium to High	No data	No data	No data	No data	At least 1

Table 5 Distribution of the municipalities of Mexico in the provision of food category

Class	Municipalities	%	VARIABLES					
			Agricultural prod (ton) *	Agricultural variety	Livestock production (ton) *	Livestock variety	Fishing prod (kg) *	Fishing variety
Very high provision	7	0.3	1,130,679	25	141,487	5	34,437,553	32
High provision	70	3	227,587	13	33,309	5	18,481,905	26
Average provision	2173	88	60,324	7	14,019	5	1,436,800	11
Low provision	199	8	4704	3	2873	3	1,901,804	8
No data/no provision	22	1	0.0	0	0	0	0.0	0

* Total production by 2020, taken from SIAP, 2020

provide food to their population, neighboring municipalities or even export food, and they have sufficient caloric and protein provision. Only 0.3% of the municipalities (8) present low availability (Table 8).

Mexico has sufficient environmental and social conditions for food production. However, its provision of these is average, and nevertheless, the amount of calories and proteins that it produces is sufficient to fulfill the needs demanded by its population. In addition, the offer that exists to obtain food in Mexico is average. That said, it is assumed that although the country has good environmental and social conditions, it does not develop its maximum potential for the production or supply of food (Figure 1).

Spatial and neighborhood analysis (global Moran index)

The results of the global Moran index (0.315) indicate that there is a positive spatial correlation between the analyzed datasets; that is, they are statistically significant. There is a notable concentration of points in quadrants I and III (Fig. 3a) that suggests a predominant concentration of similar values of food availability. The areas with the most significant values are presented in the center of the country (Fig. 3b).

The positive value of the Moran index suggests that the spatial distribution of the high values and the low value of availability is more spatially clustered than could be expected if the underlying spatial processes were random. The spatial correlation between the availability of food in a municipality and its neighbors is presented in Fig. 4.

Table 6 Distribution of the municipalities of Mexico in the caloric and protein category

Class	Municipalities	%	VARIABLES	
			Calorie coverage (%) *	Protein coverage (%) *
Very high sufficiency	1976	80	100	100
High sufficiency	165	7	65	80
Medium sufficiency	207	8	31	60
Low sufficiency	101	4	6	20
No data/no sufficiency	22	1	0	0

* Refers to percentage of population coverage for calories and proteins

Discussion

Food security in Mexico is a problem which requires an interdisciplinary approach. Our results show evidence that there is no problem with food availability, as presented in other studies [44–46]. This is because two-thirds (66%) of the municipalities have high food availability and 32% more have very high availability. As for the municipalities with low food availability (2%), they are mostly located in the state of Chiapas, similar to what was found by Aguilar-Estrada et al. [34]. This is despite the efforts of federal social programs aimed at eliminating this condition in the state [47]. Food insecurity in the southern region of Mexico is also reflected in serious public health problems, particularly among children. Minors who are severely food insecure have a higher prevalence of anaemia compared to food secure households [48].

According to research, the global food industry produces enough food for the world's population and employs more than 22 million people [49]. It has been emphasized that the world has the capacity to produce enough food to feed one person for one year on 0.045 hectares of arable, land through sustainable intensification of agro-ecosystems [50]. In addition, with sustainable practices, it has been found that food production could support 10.2 billion people within planetary boundaries, indicating significant potential for improving global food availability [51].

The food supply results show that 78% of the country's municipalities have a medium–high supply. This indicates that even in municipalities with no food production, food is available. Food is accessed through grocery stores, supermarkets and tianguis, which are very common in the country. However, this can lead to households in different areas of the country having a less diverse diet, based mainly on the consumption of

Table 7 Distribution of the municipalities of Mexico in the food supply category

Class	Municipalities	%	VARIABLES			
			Point of sale coverage (%) *	Market coverage (%) *	Market coverage (%) *	Inaccessibility (%)
Very high offer	224	9	100	65	72	2.6
High bid	1113	45	80	41	45	6.7
Average offer	789	32	75	29	38	19.8
Low offer	345	14	39	21	34	42.6

* Refers to percentage of population coverage

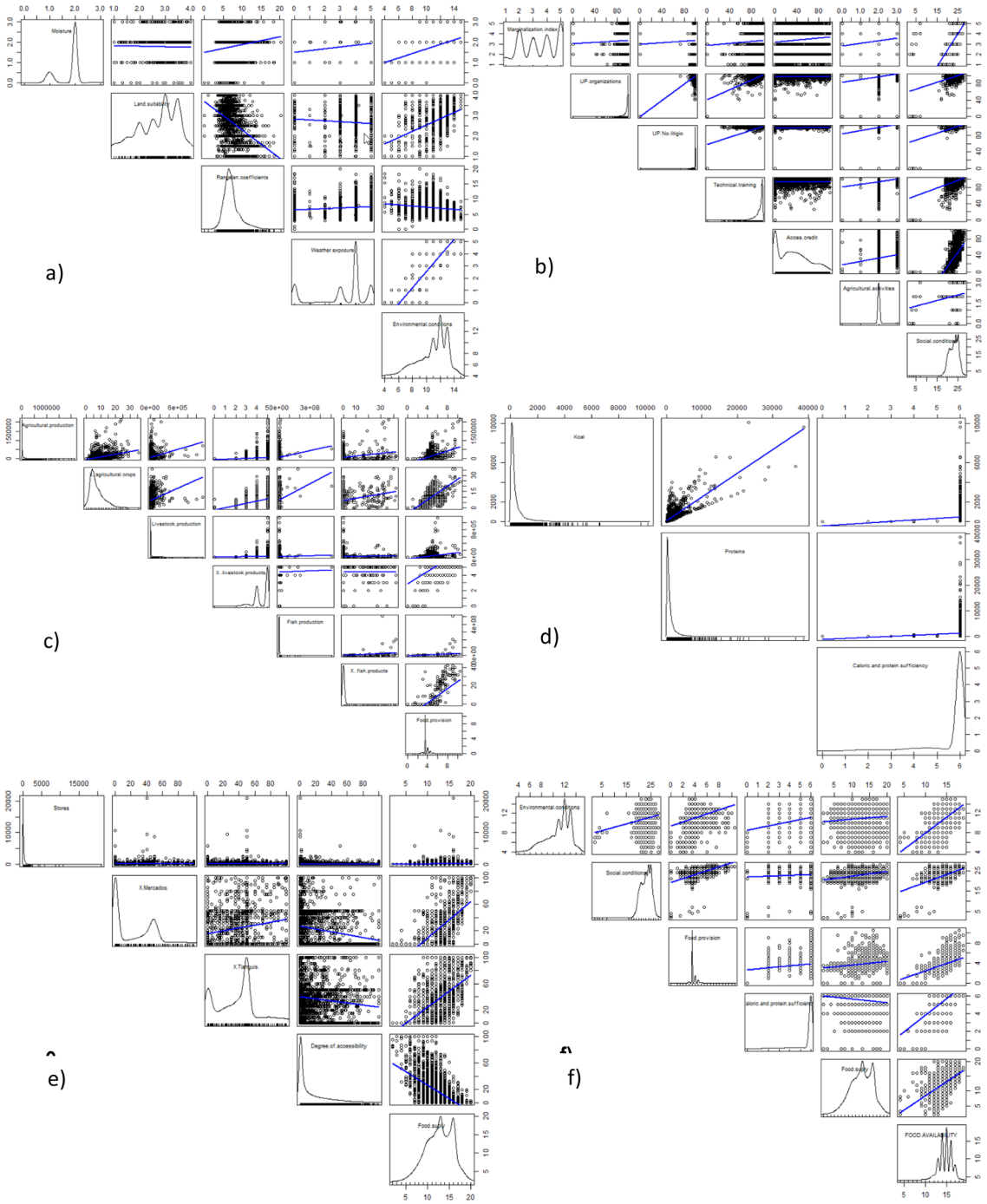

Fig. 2 Correlation between variables and subindicators **a** environmental conditions for production, **b** social conditions, **c** food supply, **d** caloric and protein sufficiency, **e** food supply and correlation between subindicators and indicator **f** food availability

cereals and low in fruits, vegetables and animal protein. Undesirable foods such as biscuits and fizzy drinks are also consumed [52]. This contributes to problems of overweight and obesity, which are linked to food insecurity and are also risk factors for developing diseases such as diabetes. This is due to the high availability of processed foods and limited access to fruits and vegetables [53].

In developed countries, several factors related to the food supply, such as the type, cost and variety of products

Table 8 Distribution of the municipalities of Mexico in the categories of food availability

CATEGORY	MUNICIPALITIES	%	Subindicator *				
			ECP	SCP	PA	CPS	FS
Very high availability of food	781	32	Very high	Very high	Medium	Very high	High
High availability of food	1634	66	High	High	Medium	Very high	Medium
Average food availability	48	2	Medium	High	Low	Low	Medium
Low availability of food	8	0.3	Medium	Low	No data/no provision	No data/no sufficiency	Medium

* (ECP) environmental conditions for production; (SCP) social conditions for production; (PA) provision of food; (CPS) caloric and protein sufficiency; (FS) food supply

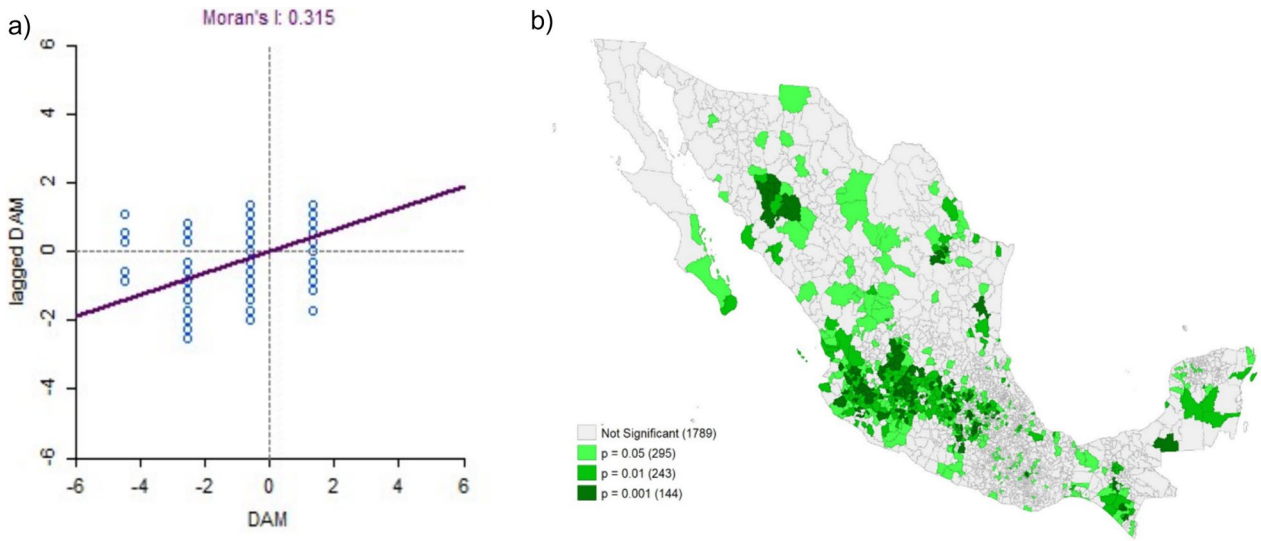

Fig. 3 **a**.Global Moran Index: DA. **b**. Significance map: DA

offered at different points of sale, have been shown to have an impact on obesity rates. Issues such as the type and concentration of food outlets, food prices, distance to food outlets and the means of transport used to reach them also play an important role [54]. The strategic location of food alternatives, such as local markets located at transportation hubs, close to homes, or along commuter routes, especially for populations without their own vehicles, has been shown to be an effective way to improve food access in underserved areas [55].

The country's food supply is sufficient when considering only the caloric and protein sufficiency produced. These results are consistent with previous studies, which state that Mexico produces more food than its population needs and is food self-sufficient [56]. However, other studies indicate a trend towards loss of food self-sufficiency, with the exception of maize and beef [33].

It will be possible to meet future food demand by increasing yields of major crops. This claim is based on the yield increases observed between 1980 and 2014, as assessed by Baldivia & Ibarra [56], assuming that there is no additional arable land for expansion in Mexico. Specifically in rural areas, subsistence farming and commercialization are variables with positive economic effects on agricultural and livestock activities, especially in backyard farming, ensuring the prevalence of family traditions [57]. It has been pointed out that the world produces enough food for the projected world population of 9.7 billion people in 2050, provided there is a radical societal shift to plant-based diets and food waste is reduced [58]

However, the increase in the price of agricultural products is attributed to the cost of transportation, which limits their accessibility despite their availability (FAO, [59]). The annual wage increase in Mexico does not counteract the rising costs of food, services, and transportation, with poverty being a determining factor in food insecurity. Although federal programs and policies such as "Oportunidades", "Procampo" and "Adulto Mayor" have contributed to a 9% reduction in poverty, there is evidence of the need for more effective alternatives [60]. According to Muñoz-[61], the high failure rate of Mexican family gardens is consistent with the prevailing policy approach, which sees the problem of food security as a 'lack of

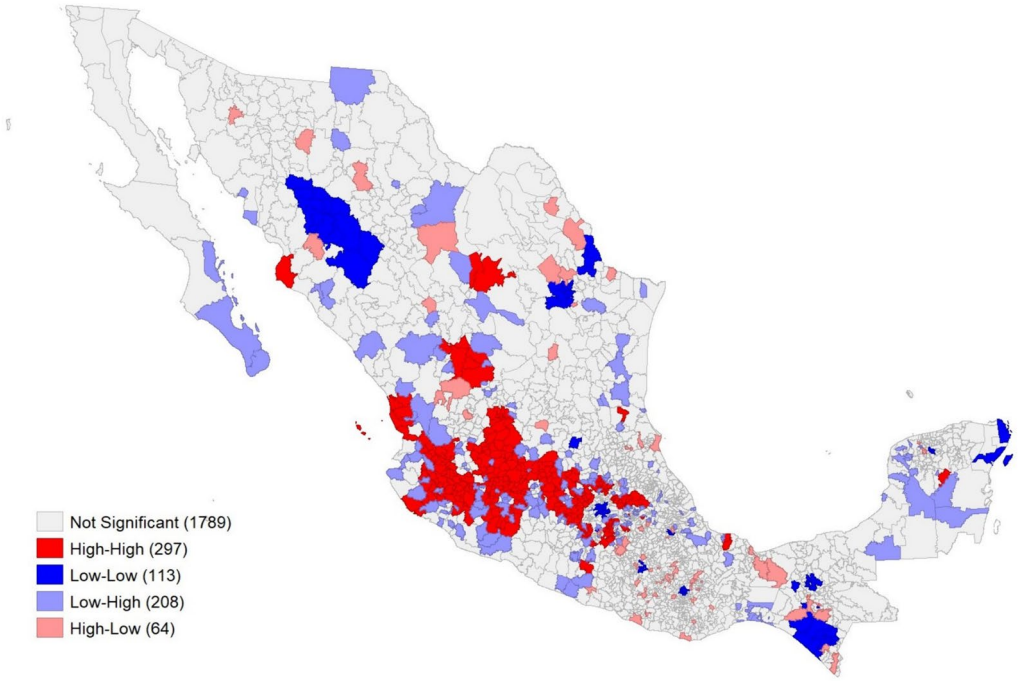

Fig. 4 Food availability index in municipalities of Mexico and correlation with neighboring municipalities. The strong red color indicates that a municipality has high availability of food and its neighbors as well. In contrast, the strong blue color indicates that a municipality has low availability of food and its neighbors as well

assets' for production. This suggests a weak link between the problem and policy.

In the United States, despite the rise in food prices, annual wage increases can help offset their impact because disposable personal income has historically risen faster than food prices, which have kept the share of food expenditures constant [62]. In India, by contrast, increasing annual wages in agriculture would require an 80% increase in crop prices in the short run to offset the wage impact, or a 140 percent increase to offset the increase in rural non-farm wages [63]. Then, raising the minimum wage can help offset the impact of higher food prices by increasing workers' purchasing power, reducing poverty, and improving overall economic stability [64].

The implementation of public policies based on the promotion of productive structures, taking into account regional differences, could be a viable strategy [65]. Small-scale studies are proving to be indispensable tools for identifying specific problems in each region and ensuring the success of tailored public policies. Despite the challenges, policy such as social grants show that cash transfers increase household income and diversify diets, contributing to food security [44, 45].

The multivariate approach of this study has been key to understanding the complex dynamics of food availability in Mexico. The integration of multiple sub-indicators allowed us to comprehensively address the factors that influence food availability at the municipal level. By contextualizing the results at the global level, opportunities for improving food policies were identified. In summary, this study offers valuable insights that can contribute to more effective strategies to promote food security in Mexico and internationally.

Conclusions

Food availability in Mexico was measured at the municipal level. The selected variables made it possible to empirically explain the availability of food in the municipalities. Based on the results, it is possible to identify some of the problems that each municipality faces: environmental, social, productive stagnation of the agricultural sector, lag of its productive structure or even the dismantling of the production base.

The results are not definitive, but it is possible to conclude that food availability is not an issue (production and distribution) in most municipalities. That is, there are moderately appropriate environmental and social conditions for production. Therefore, the issue of food insecurity in Mexico is influenced by additional factors that warrant a more thorough analysis. Hence, the need for a deeper exploration of the underlying elements

contributing to food insecurity in the Mexican context becomes evident, taking into account broader and more complex aspects of its socio-economic structure. This and the other dimensions of food security should be studied further at the same municipal scale. This will allow for a more in-depth identification of the problems so they can be addressed more directly.

One of the main limitations encountered in this study was the difficulty in accessing data at small scales, particularly at the municipal level. It is therefore recommended that any attempt to replicate this methodology should ensure the availability of information on the variables used at the appropriate scale.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-024-00484-2.

Supplementary material 1

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Author contributions
Authors YCS and AIMR conceptualized the study and did the first write-up. Author YCS designed the data collection tools and most of the analysis. Authors AAE and JBM contributed to the review and overall supervision of the research. All the authors read and approved the final manuscript.

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Availability of data and materials
The first author will provide data upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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The authors declare that they have no conflict of interest.

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