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DOCTORADO EN CIENCIAS EN AGRICULTURA MULTIFUNCIONAL PARA EL DESARROLLO SOSTENIBLE

EVALUACIÓN DE LA SOSTENIBILIDAD A BASE DE RESILIENCIA INTEGRAL DE HUERTOS FAMILIARES EN EL TOTONACAPAN, MÉXICO

TESIS

Que como requisito parcial para obtener el grado de:

DOCTOR EN CIENCIAS EN AGRICULTURA MULTIFUNCIONAL PARA EL DESARROLLO SOSTENIBLE

Presenta:

INDUMATHI RAJAGOPAL

Bajo la supervisión del:

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Enseñar la explotación de la tierra, no la del hombre

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DOCTORAL PROGRAM OF SCIENCE IN MULTIFUNCTIONAL AGRICULTURE FOR SUSTAINABLE DEVELOPMENT

EVALUATION OF THE SUSTAINABILITY BASED ON INTEGRAL RESILIENCE OF HOMEGARDENS IN TOTONACAPAN, MEXICO

THESIS

That as a partial requirement to obtain the degree of:

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Presents:

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Evaluation of the sustainability based on integral resilience of homegardens in Totonacapan, Mexico

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DEDICATIONS

To my second home, Mexico!

To my knowledge center, Chapingo Autonomous University!

To my community, the members of Santiago Ecatlan, Jonotla, Puebla!

To my compassionate and inspiring brother, Mr. R. Rajasekaran!

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GENERAL ABSTRACT

Evaluation of the sustainability based on integral resilience of homegardens in Totonacapan, Mexico*

Traditional agroecosystems, including homegardens (HGs), face various natural and anthropogenic alterations derived from adverse modifications in the current environment, economic, and sociocultural conditions. Consequently, the resilience and sustainability of these evidenced in some rural communities in Mexico are put at risk. This study aimed to evaluate the current degree of integral resilience of homegardens in the study area to determine their degree of sustainability. A sample of 12 homegardens was selected in the Totonac community of Santiago Ecatlan, Puebla. Data were collected from thirty members of different age groups during June 2018-July 2019. A conceptual framework of resilience was developed based on the hypothesis that the higher the magnitude of agrodiversity, the higher the integral resilience of homegardens. A methodology was adapted to operationalize the framework in which the resilience index was elaborated using qualitative and quantitative methods, and multi-criteria analysis of FlowSort was carried out to evaluate the sustainability of the HGs based on their resilience category. The results show that orchards no° H1, H4, H5, and H2 registered the highest resilience index (RI). Garden H10 reported the lowest RI, without differentiating from H8 and H9. The FlowSort analysis showed that H1, H2, H4, and H5 orchards belong to the high resilience category, while the rest belong to the medium resilience category. Finally, the orchards that belong to the high resilience category were evaluated as potentially sustainable. To conclude, homegardens with high agrobiodiversity, management and conservation capacity, monetary gains, and organizational capacity contribute to increasing ecological, economic, and cultural resilience in the face of adverse challenges. Thus, the more significant the transmission, conservation, and improvement of agrodiversity associated with homegardens and the degree of appreciation for it by current and future generations, the greater the integral resilience and sustainability of Totonacapan homegardens.

Keywords: agrodiversity, agroforestry, biocultural heritage, inclusive development, multifunctional agriculture, traditional knowledge.

*Thesis, Ph D. in Science in Multifunctional Agriculture for Sustainable Development, Chapingo Autonomous University. Author: Indumathi Rajagopal.
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RESUMEN GENERAL

Evaluación de la sostenibilidad a base de resiliencia integral de huertos familiares en el Totonacapan, México*

Los agroecosistemas tradicionales, incluyendo los huertos familiares (HFs), enfrentan actualmente diversas alteraciones naturales y antropogénicas derivadas de modificaciones adversas. en las condiciones ambientales, económicas y socioculturales. En consecuencia, ponen en riesgo la resiliencia, así como la sustentabilidad de éstos evidenciada en algunas comunidades rurales de México. Este estudio tuvo como objetivo evaluar el grado actual de resiliencia integral de los huertos familiares en el área de estudio como base para determinar su grado de sostenibilidad. Se seleccionó una muestra de 12 huertos familiares en la comunidad totonaca de Santiago Ecatlán, Puebla. Se recolectaron datos de treinta miembros de diferentes grupos de edad durante el período de junio de 2018 a junio de 2019. Se desarrolló un marco conceptual de resiliencia basado en la hipótesis de que cuanto mayor es la magnitud de la agrodiversidad, mayor es la resiliencia integral de los huertos familiares. Se adaptó una metodología para operacionalizar el marco en el que se elaboró el índice de resiliencia utilizando métodos tanto cualitativos como cuantitativos. Se realizó un análisis multicriterio de FlowSort, para evaluar la sostenibilidad de los HFs en función de su categoría de resiliencia. Los resultados muestran que los huertos no° H1, H4, H5, y H2 registraron los índices de resiliencia (IR) más altos. El huerto H10 registró el IR más bajo, sin diferenciarse de H8 y H9. El análisis de FlowSort mostró que los huertos H1, H2, H4 y H5 pertenecen a la categoría de alta resiliencia, mientras que el resto pertenece a la categoría de resiliencia media. Finalmente, los huertos que pertenecen a la categoría de alta resiliencia fueron evaluados como potencialmente sostenibles. Para concluir, los huertos familiares con alta agrobiodiversidad, capacidad de gestión y conservación, ganancias monetarias y capacidad organizativa, contribuyen a aumentar la resiliencia ecológica, económica y cultural frente a desafíos adversos. Así, cuanto más significativa sea la transmisión, conservación y mejoramiento de la agrodiversidad asociada a los huertos familiares y el grado de aprecio de la misma por parte de las generaciones actuales y futuras, mayor será la resiliencia integral y la sostenibilidad de los huertos familiares del Totonacapan.

Palabras clave: agrodiversidad, agroforestería, patrimonio biocultural, desarrollo incluyente, agricultura multifuncional, conocimiento tradicional.

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1. GENERAL INTRODUCTION

The increasing human impact on ecosystems jeopardizes the biophysical process and functions of our planet. Notably, the effect of unsustainable or harmful agricultural practices (such as excessive use of toxic agrochemicals, single-crop production, the irrational expansion of the agrarian frontier, as well as the loss of various cultural aspects associated with respectful management of nature) on natural resources endangers ecosystem sustainability (Carson, Darling, and Darling, 1962; Food and Agriculture Organization of the United Nations [FAO], 2017b).

Consequently, environmental challenges such as climate change, land degradation, deforestation, soil depletion, freshwater scarcity, loss of biodiversity, ocean acidification, and eutrophication threaten millions of the planet's species (Sachs, 2015; FAO, 2017a). Mainly, food security has become a growing challenge, considering that the number of food-insecure people has increased globally for the past four years. COVID-19 has further exacerbated this situation by affecting vulnerable households in almost every country (World Bank, 2021).

Besides, as environmental performance and human well-being go hand in hand, humanity pays a cost for overexploiting the natural environment (Everett, Ishwaran, Ansaloni, and Rubin, 2010). Due to the above-mentioned environmental challenges, many people still live in an unequal world facing immense socio-economic crises. Food insecurity is on the rise mainly due to climate change and conflicts for vital natural resources (FAO, 2019). Also, the culture associated with the perception, management, use, and conservation of plant resources is being lost, which is, in some cases, faster than the loss of agrobiodiversity itself (Cuevas pers. com, 2019).

In addition to these challenges, the growing human-induced environmental, socioeconomic, and cultural changes are not only reshaping Earth's natural ecosystems but also influencing the ability or the resilience of the existing agricultural systems to withstand external or internal shocks and stresses. Thereby their very own structure and function are threatened, which endangering these systems' sustainability. Thus, it raises a critical question: how will food security be achieved with a growing population, the increasing magnitude of climate hazards, human conflicts, and pandemics?

Under these circumstances, as attaining sustainable development is the priority of the global agenda, building or strengthening the resilience of the existing agroecosystems at different spatial and temporal scales to confront the above global trends is essential. Hence, the real challenge is how to meet the demands of the growing population through resilient human food production or agricultural systems without crossing the thresholds of the planetary boundaries to achieve sustainable development (Folke, 2006; Rockström *et al.*, 2009a).

Particularly, homegardens can offer a solution for the most vulnerable households from the context of food security by conserving biocultural diversity at a local scale. In summary, the principal question to build a sustainable era is how to ensure the long-run resilience of the agro-ecosystems and human well-being without neglecting to safeguard the natural capital for future generations (Folke, 2006; Rockström *et al.*, 2009a & 2009b; Bouma and Van Beukering, 2015).

In this context, traditional agroecosystems such as homegardens are recognized for their sustainable management and use of natural resources (Conklin, 1954; Martínez-Ballesté and Caballero, 2016), they could play a significant role in promoting sustainable agriculture through resource-use efficiency of Earth's finite resources (FAO, 2017b). For example, Rappaport (1971) stated that "the ratio of the yield to energy input was about 16.5 to one kilocalorie (kcal) for the taro-yam gardens and about 15.9 to one kcal for the sweet potato gardens", and the author argued that if the distance reduced between orchards and residence of the Tsembaga during the festival of the year 1963, the yield ratio would have risen respectively to 20.1 and 18.4 to one kcal in taro-yam and sweet potato gardens.

Also, the author of the study concluded that the obtained energy output was more significant than energy input for management in traditional agroecosystems.

Moreover, the biocultural knowledge (accumulated and transmitted through generations) involved in these systems could significantly mitigate the adverse effects of unsustainable agricultural practices and contribute to food security for the local people. According to and agreeing with the personal communication of Cuevas (2019), however, as the mere existence of such heritage is not enough to promote the resilience of agroecosystems, it is also required that those who inherit such heritage should appreciate and consider it when making decisions about the management, use, and conservation of the natural resources associated with it. Likewise, the less reliance on products derived from fossil energy in the traditional agroecosystems than commercial agricultural systems implies less ecological and economic cost and more positive externalities, contributing to a high degree of sustainability.

Although traditional agroecosystems such as homegardens are considerably recognized for their potential to enhance the well-being of the local people as well as to promote sustainable development, currently, these traditional farming systems are vulnerable to various environmental, economic, and socio-cultural crises (such as cultural erosion, migration, land-use change, loss of agrobiodiversity, climate change), particularly in the rural parts of Mexico (Kumar and Nair, 2006; Boege, 2008; Mohri *et al*., 2013; Vogl-Lukasser and Vogl, 2018).

1.1 Statement of the research problem

Homegardens (HGs) predominate in many parts of the world in different cultures. Notably, homegardens are widely prevalent and play a vital role in the livelihood of the indigenous people living in the rural landscapes of Mexico (Kumar and Nair, 2004, 2006; Mariaca, 2012). However, the current adverse environmental, socioeconomic, and cultural changes (derived from the natural and anthropogenic alterations of the biophysical processes and functions of the Earth systems) significantly influence national agriculture, including traditional agroecosystems such as HGs. Consequently, it promotes reducing the resilience associated with these systems, thereby putting their sustainability at risk (Rajagopal *et al*., 2021).

In other words, despite HGs prominence, the current human-induced adverse global environmental, economic, and socio-cultural changes are leading the existing traditional homegardens into a vulnerable situation and deteriorating the livelihood of millions of people who depend on them. As a result, many indigenous people are forced to abandon the long-practiced subsistence farming systems searching for a "better" social and economic opportunity (Mohri *et al.*, 2013, Cano Contreras, 2015; González, 2018).

The discontinuity of these traditional farming practices threatens the provisioning of ecosystem services and significantly affects the overall sustainable rural development of the native people. Besides, the sustainability of these systems itself threatened in the face of the current adverse global challenges, including climate change, degradation of natural resources, and the acculturation process (Mohri *et al.*, 2013, Cano Contreras, 2015; González, 2018; Ordoñez Diaz, Benjamin Ordoñez, and Lope-Alzina, 2018; Rajagopal *et al*., 2021).

Based on the above lines of thought, it is essential to study, revalue, fortify, and promote existing traditional land-use practices as one of the viable strategies to contribute to sustainable development at the local scale. For this, it is essential to analyze homegardens sustainability based on their degree of resilience, i.e., the system's capacity to return to the steady-state or adapt and transform into new conditions to reach new states after disturbances (Walker, Holling, Carpenter, and Kinzig, 2003). For instance, how idiosyncratic shocks (such as death, illness, migration of the family labor) or covariate shocks (such as cultural erosion, changing weather patterns) influence the fundamental structure and functions of homegardens.

The studies regarding understanding the integral (ecological, economic, and sociocultural) resilience of homegardens based on the holistic approach of multifunctional agriculture and ethnobotanical aspects lack in Mexico. The existing current models to evaluate sustainability are mainly based on productivity, i.e., the quantity of production and the economic viability of the net output (Rajagopal *et al*., 2021). Furthermore, despite the contributions derived from the existing research protocols, it is necessary to deepen the development of techniques that measure the cultural aspects of managing traditional agroecosystems with greater objectivity. In short, the focus of this study is to assess the degree of resilience and the sustainability of homegardens prevalent in the study area with Totonac culture. In this context, the present study aims to elucidate the following research questions:

- How to measure the degree of integral (ecologic, economic, and sociocultural) resilience of homegardens? And how does it influence the sustainability of homegardens in the study area?
- What are the main variables involved? And how do they explain the integral resilience evidenced between the studied homegardens and their sustainability?
- What variables could explain the role and magnitude of the agrodiversity (management, use, and conservation of resources) involved in the studied homegardens?
- What are the recommended collective actions to enhance the integral resilience of homegardens in the study area?

1.2 Research justification

While considering the current adverse global trends, there is an essential need to implement multiple strategies to reduce humankind's negative impact on ecosystems. Thus, confronted with this situation, scientists emphasize the need for a new model of sustainable agriculture with a multifunctional nature that aims to produce food and provide non-food products to conserve ecosystem functions and services (Beverly, Herren, Wakhungu, Judi, and Watson, 2009).

Also, development strategists and agronomists stress the need to explore alternative strategies to meet productivity demands and preserve the natural resource base. Some agronomists suggest shifting our focus to examine and transform the existing food systems based on holistic approaches such as agroforestry, climate-smart agriculture, agroecology, and multifunctional agriculture. Others suggest revaluing, fortifying, and promoting the integrated traditional agroecosystems or farming systems based on indigenous knowledge such as family agriculture and homegardens that commonly predominate in rural areas, particularly among local ethnic groups enhance the livelihoods of local people (FAO, 2017b).

Given the above aspects, in recent years, the role of traditional agroecosystems such as homegardens has been recognized worldwide (Kumar and Nair, 2006; Mariaca, 2012; Agbogidi and Adolor, 2013; Galhena, Freed, and Maredia, 2013; Ordoñez-Diaz *et al*., 2018; Rajagopal *et al*., 2021). Also, goals have been set for strengthening and recovering them. As the traditional homegardens can play a crucial role in achieving sustainable development in the local setting and are predominant among indigenous people in rural parts of Mexico, it is necessary to carry out comprehensive studies based on an integral approach that allows us to understand their dynamics.

Besides, as the ability of the traditional agroecosystems such as homegardens to cope up with the current global environmental threats and socio-economic challenges is not well-defined until now, therefore, it is essential to study the role of agrodiversity (i.e., aspects relevant to management, use, and conservation of resources) present in the homegardens, to evaluate its integral resilience as well as its sustainability based on the holistic approach of multifunctional agriculture and ethnobotany (Rajagopal *et al*., 2021).

In this context, the current study focuses on evaluating sustainability based on the degree of integral resilience of homegardens. And the present research proposed designing a conceptual and methodological framework of measuring the self-regulation (resilience) mechanism based on selected ecological, economic, and socio-cultural indicators. Since few studies are relevant to the above study problem, this proposed homegarden research will contribute to sustainable development from the perspective of multifunctional agriculture and ethnobotany.

Besides, this study intends to fill the gap in the literature to assess the sustainability of traditional agroecosystems such as homegardens with lower economic benefits than commercial or conventional agroecosystems. This, in turn, could facilitate the implementation of alternative adaptation strategies for sustainable development at the family or local scale in similar ecological, socioeconomic, and cultural backgrounds.

The research was carried out in Santiago Ecatlan, in the municipality of Jonotla, State of Puebla. The selection of the study area would represent the indigenous group (Totonac), one of about 68 ethnic groups in Mexico who practice traditional homegardens in different regions of Mexico. This study will also facilitate understanding the critical cultural factors involved in managing the Totonac homegardens that significantly influence the degree of resilience and the sustainability of the study units.

Besides, the study area is located within the RTP (*Regiones Terrestres Prioritarias*, i.e., Priority Land Regions) of Mexico established by the (*Comisión Nacional para el Conocimiento y uso de la Biodiversidad)* CONABIO (Arriaga *et al.,* 2000). Therefore, it is essential to analyze the traditional agroecosystems of the study area to conserve biocultural heritage and achieve sustainable rural or bottom-up development.

1.3 General hypothesis

- Due to the problem stated in the present chapter, the current research hypothesis postulates that the agrodiversity (including ecological and cultural aspects) associated with homegardens and the degree of appreciation towards it are the main aspects that determine the degree of resilience and sustainability of the local homegardens. Therefore, this research established the following objectives to verify this hypothesis.

1.4 General objective

- To assess the current degree of integral resilience of homegardens in the study area as a basis for evaluating their sustainability.

1.4.1 Specific objectives

- To analyze the main variables involved in the ecological, economic, and socio-cultural resilience evidenced by the homegardens considered in the present study.

- To evaluate the magnitude, composition, and cultural significance of the agrodiversity involved in the homegardens in the study area.

- To identify collective actions that could be implemented to increase the integral resilience of the studied homegardens and, thereby, their sustainability.

1.5 Summary

Based on the above and considering the complexity of the issue involved in understanding the integral dynamics of homegardens (HGs), this dissertation was divided into eight chapters. Starting from a general introduction (including brief background information, statement of the research problem, justification, hypothesis, general and specific objectives) related to the scope of this research (Chapter 1), we proceeded to the conjunction of the conceptual framework

(Chapter 2) pertinent to the understanding of the integral dynamics (ecological, cultural, and economic) of the HGs, emphasizing those existing in Mexico. To be specific, this chapter is dedicated to reviewing different topics related to current research exploring both global and national contexts. Also, to facilitate the readers understanding, this chapter is divided into several sections, that outline in general, the current global challenges and their impact on agricultural systems, the importance of traditional agroecosystems, general concepts and their relevance to this research, and the theory, as well as the existing methodologies, applied to measure resilience involved in agricultural processes. In Chapter 3, state-of-the-art related to the study topic (i.e., homegardens for sustainable development) was integrated and analyzed, which involved comparing 335 scientific articles published between 1986 and 2020 in high-level journals. Chapter 4 refers to the analysis of the structure and function of agrodiversity, which, considered as the most intangible heritage in rural Mexico, involves, in addition to multiple plants, animal, and microorganism *taxa*, various cultural aspects related to the perception, vernacular classification, use, and conservation of genetic resources, particularly plants. In Chapter 5, different methods applied to evaluating the resilience involved in the measurement of the degree of sustainability evidenced by a set of homegardens located in the selected community to carry out this study are analyzed. In Chapter 6, the limitations of the current study are presented. Finally, chapter 7 establishes the general conclusions derived from this research, dedicating Chapter 8 to recommend actions to enhance the resilience of HGs in Totonacapan.

2. CONCEPTUAL FRAMEWORK

According to Hernández (1970), the first experience involved in the ethnobotany exploration is: There are always antecedents, whatever the problems to be studied. Based on the above line of thought, the present chapter examines various topics to provide the essential literature background for this research. Hence, the following issues are analyzed using an extensive literature review to comprehend the global and national context of 1) Planetary boundaries and the impact of human activities; 2) Global environmental impacts on food and agricultural systems; 3) The global state of socio-economic and cultural challenges; 4) Towards a sustainable future through multifunctional agriculture; 5) Promotion of traditional agroecosystems for sustainable livelihoods; 6) General concepts relevant to the current research; 7) Resilience theory and sustainable development; 8) Diverse approaches to assess resilience, and 9) Review of other methods considered in this study. All the topics mentioned here are presented in the following sections:

2.1 Planetary boundaries and the impact of human activities

Planetary boundaries refer to the concept involving Earth system processes that contain environmental limitations. Understanding the planet's ecological limits to sustain life and the impact of agricultural activities on ecosystems is essential to design and implement strategies to build resilient and sustainable farming systems, including homegardens.

2.1.1 The global state of the unprecedented environmental crisis

There is an urgent need for a paradigm that integrates the continued development of human societies and the maintenance of the Earth System (ES) in a resilient and accommodating state. Long-term global sustainability and human well-being depend primarily on the capacity of the ES to sustain ecological functions and provide ecosystem services. For instance, healthy ecosystems provide clean air, water, food, and other services or benefits to humankind, fundamental for its survival and well-being (Millennium Ecosystem Assessment [MEA], 2005).

But, since the new epoch of the Anthropocene, humans have become dominant drivers of planetary change (Crutzen, 2002 & 2006). Primarily, since the past three centuries, thanks to the advances made in science and technology, enormous economic progress has been achieved worldwide. However, much of humanity's growth has come at a considerable cost to the environment (FAO, 2017a). This is mainly due to the interactions between the coupled human and environmental systems: complex, non-linear, and reciprocal. The adverse impact among these systems influences each other, significantly contributing to the collapse of the ecosystems' vital ecological functions and poses a severe socio-economic challenge to humanity (Turner *et al*., 1990; Liu *et al.,* 2007; Rockström *et al*., 2009a; Rockström, 2015; Steffen *et al*., 2015).

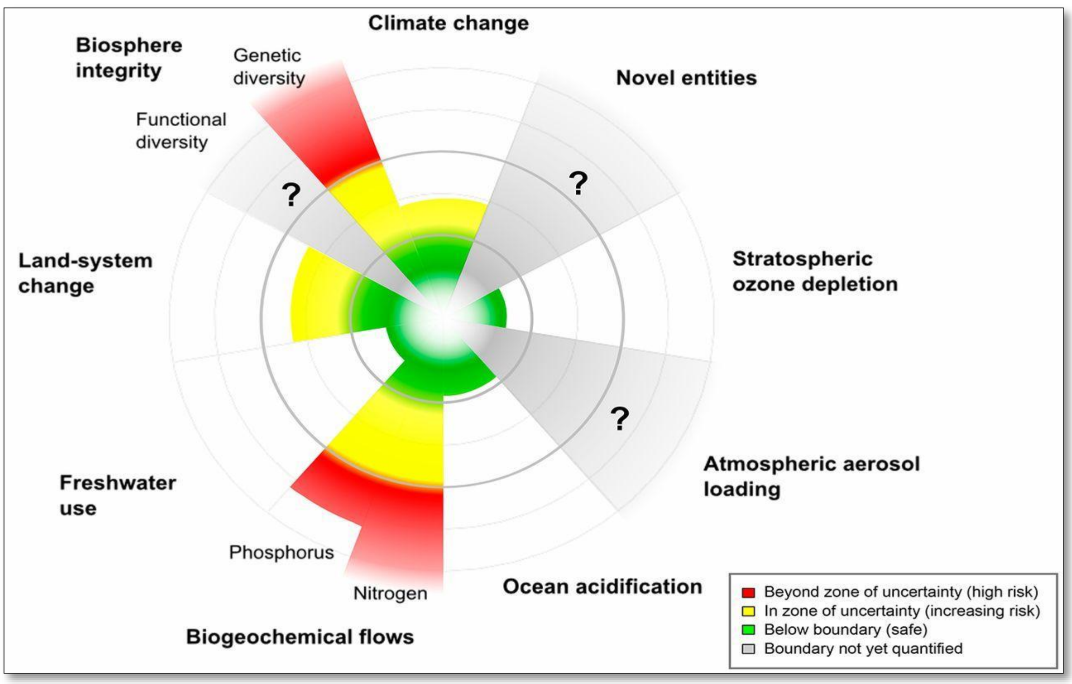

Figure 1.Planetary boundaries of the Earth's systems.

(Source: Steffen *et al*., 2015).

To be specific, human activities not only alter ecosystems (MEA, 2005) but cross certain biophysical thresholds of planetary boundaries. And scientists argue that humanity has already transgressed four (climate change, biosphere integrity, i.e., genetic and functional diversity, land-system change, nitrogen, and phosphorus levels) out of nine planetary boundaries (Figure 1). Trespassing these boundaries could disrupt the known stability of the Holocene state of the ES, where living conditions to human development were favorable (Rockström, 2015; Steffen *et al*., 2015).

Due to the industrial revolution (that significantly contributed to the exponential growth of the human population), the added demand for natural resources to satisfy the needs of the growing population increased human activities that altered the natural environment where humanity thrives. Besides, the expected population growth of ten billion by 2050 will positively accelerate anthropogenic pressures and the competition for natural resources (Sachs, 2015).

Thus, in summary, the growing human impact on the environment is triggering abrupt and irreversible changes in the ES. These unacceptable changes have an immediate effect and could disrupt the social-ecological resilience of the ecosystems as well as the agroecosystems (human-modified ecosystems for agricultural purposes). Moreover, they pose a higher risk to humanity in the planet's transition from the Holocene to the Anthropocene (Rockström *et al.*, 2009b; Steffen *et al*., 2015).

2.1.2 The impact of agriculture on ecosystems

The advent of agriculture, about 10,000 – 12,000 years ago (Trabanino, 2018), has not only facilitated human beings to produce their food and satisfy their basic needs but has given way to the rise of complex societies and human civilization. However, since the industrial revolution, agriculture is one of the economic sectors with an equal or more significant adverse impact on natural resources than other industries. Therefore, advances in agriculture are inevitably associated with alterations of natural ecosystems (FAO, 2017a).

As the elements of agriculture and ecosystems are necessarily linked to each other by using the same natural resources (such as soil, water) based on the same biological processes (such as photosynthesis, biomass production), the progressive control and intensification of natural resources used to increase food production have triggered negative feedback on the whole environment. For instance, Ramankutty *et al.* (2018) state that the current global environmental crisis such as deforestation, degradation of land, soil erosion, biodiversity loss, climate change, water scarcity, eutrophication, etcetera has resulted primarily from agricultural activities.

Ironically, recent technological progress aimed to increase global outputs of the food production systems and efforts to produce resource-intensive bioenergy (instead of using more sustainable energy sources) have led to further intensification of the competition for natural resources and the degradation of ecosystems (FAO, 2017a).

According to FAO (2020), about 37.6% (4,889 out of 13,003 million hectares) of the total land area is used for agriculture. In other words, agriculture dominates nearly half of the habitable land, i.e., around 51 out of 104 million km^2 (Ritchie, 2019). Remarkably, the intensification and expansion of agriculture in the last few decades, especially from the green revolution, triggering significant detrimental impacts on the Earth's physical systems. Specifically, the irrational land conversion for agriculture is one of the significant impacts on ecosystems that transform habitats and triggers immense biodiversity loss.

Nevertheless, by 2050, a growing population will need to produce twice as much food as 2000 but will have to use the same natural resources and other inputs. Notably, an additional one billion tons of cereals will be needed annually by 2050. Furthermore, the demand for grain to feed livestock and produce bioenergy also contributes to the above global scenario (FAO, 2019). Therefore, there is an urgent need to intensify food production levels in the near future.

Alexandratos and Bruinsma (2012) and FAO (2017a) conclude that the intensified competition for these resources for agriculture degrades the environment due to overexploitation and creates a negative feedback loop. This, in turn, increases further competition for the remaining available resources and triggers further degradation of both resources and the environment. Thus, the persistence of current trends in the immediate future will lead to natural resource scarcity for agriculture in 2050 and undermine the overall sustainability of the environment.

Hence, the above-mentioned vicious cycle of the adverse impacts between the coupled human and environmental systems is inevitable unless strategies are employed or enforced to promote traditional agroecosystems and sustainable multifunctional agriculture. However, it is essential to remember that even though traditional practices could serve as one of the alternative strategies to face the current crisis, the satisfaction of human necessities also requires enhancing the agricultural frontier. Still, the crucial question is how to do it within the limits of the ES?

2.2 Global environmental impacts on food and agricultural systems

Even though agricultural systems are one of the significant sources of ecosystem degradation, the productivity and resilience of these agroecosystems themselves, severely affected due to the current adverse environmental challenges that undermine the sustainable livelihoods of millions of people (Ramankutty *et al.,* 2018), the following are some of the global ecological trends that have massive impacts on farming systems, including homegardens.

2.2.1 Erosion of agro-biodiversity

Genetic diversity of crops and livestock (the primary source of food and other critical anthropocentric resources) is fundamental to the livelihood of the human population to achieve food security and economic development. However, currently, on the one hand, the overall biodiversity of our planet is dramatically reduced due to the modifications of global biomes through human actions (MEA, 2005), on the other hand, the loss of agricultural biodiversity or agrobiodiversity is also escalating (Biodiversity international, 2017).

Notably, the genetic erosion (within-species diversity of crop and livestock) in many parts of the world (due to the shift from farmer's varieties or landraces to new genetically modified types or breeds) leads to genetic vulnerability of the widely planted crops and livestock susceptible to pests, pathogens or environmental hazards as a result of their genetic constitution. For example, the loss of Irish potatoes (1845-1849) due to pests, avian flu, etc.

In other words, as farms are becoming less diverse (in terms of the ecosystems, species, and within-species genetic resources they comprise), the genetic erosion of plant and livestock species reduces options for the agricultural sector and increases the vulnerability of the farmers in front of climate change, pests and diseases (FAO, 2010; FAO, 2015b).

According to the FAO reports (2019), global livestock production is based on about 40 animal species, out of which only a handful provides meat, milk, and eggs. About 26% of the 7,745 local breeds of livestock reported globally are at the risk of extinction. Furthermore, out of 6,000 plant species cultivated for food, only 200 contribute to the global food output, and only nine varieties of plants account for 66% of the total crop production.

Also, nearly a third of the worldwide fish stock is over-cultivated, and more than half has already reached its sustainable limit. The report also reveals that the actual and potential value of several wild plant species to meet the food and nutritional demand are also lost in the process of land-use change even before it is identified (FAO, 2019).

Besides, the wild food species and many contributing species vital to food and agriculture, including pollinators, soil organisms, and natural enemies of pests, also disappear at a highly rapid pace. Many species that belong to the associated biodiversity are also under severe threat. Birds, bats, and insects help control pests and diseases; wild pollinators like bees and butterflies all belong to this category (Schrader Franzén, Sattler, Ferderer, and Westphal, 2017; FAO, 2018; FAO, 2019).

The most significant numbers of declining wild food species belong to Latin America and the Caribbean, with Africa and Asia-Pacific following them. For example, although Mexico is considered as a “mega bio-diverse” country that possesses more than 10% of the world’s biological diversity (Jiménez *et al.,* 2014; Zorilla-Ramos and Cruz-Angón, 2014), and occupies fourth place in the world due to its floristic richness (Table 1) with high level (49.8%) of endemism, only 120 out of 23,314 vascular plant species have been domesticated as food plants (Villaseñor, 2016), of which, only 25-30 are highlighted as significant crops of importance based on its global production and economic criteria. Moreover, barely three crops (corn, wheat, and rice) dominate more than 60% of the country’s land (Sarukhán *et al.*, 2017). In brief, agrobiodiversity for food and agriculture is indispensable to achieve sustainable development. However, its decline spells trouble for the future of food production systems.

Table 1. Plant diversity in Mexico.

Vascular plants (Traqueophytes)	
Orders	73
Families	297
Genera	2,854
Species	23,314
Species with seeds (Spermatophytes)	
Gymnosperms	149
Angiosperms	22, 126
Species without seeds (Pteridophytes)	
Ferns and Lycophytes	1,039
No vascular plants (Talophytes)	
Mosses and liverworts	1,482
Algae	2,702
Total no vascular plants	4,184
Total plant species (23,314+4,184)	27,498

(Source: Villaseñor, 2016).

2.2.2 Global warming and climate change

Global warming and climate change pose enormous threats to food production systems and could affect the livelihoods of millions of people who depend on agriculture, especially in low latitudes. In contrast, effects on production in northern latitudes could be either positive or negative (Porter *et al.*, 2014).

However, changing weather patterns (temperature, rainfall, humidity, and other factors) due to global warming are disrupting farming activities already and will have massive impacts on crops, livestock, and fisheries production (Campbell *et al.*, 2016). According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) 2014, the global average surface temperature will likely increase between the ranges of 0.3°C and 4.8°C by the end of the 21st century (2081-2100). If the prediction is correct, higher temperatures could exceed crop-specific levels and inevitably reduce crop yields, especially in low and middle-income countries of the tropics than high-income countries located in temperate zones.

A meta-analysis of 1090 studies on yields or returns conducted by the Food and Agricultural Organization (FAO) indicates that climate change may significantly reduce yields of some principal crops such as wheat, maize, rice, and soybeans, in the long run (Porter *et al.*, 2014; FAO, 2018). Challinor *et al.* (2014) state that on average global mean crop yields of rice, maize and wheat will decrease between 3% and 10% per degree of warming above historical levels.

Another study in China found that nonlinear and inverted U-shaped relationships exist between crop yields and weather variables (Chen, Chen, and Xu, 2015). China's corn and soybean sectors have lost more than the US $820 million in the past decade due to global warming and expect to decline 3-12% of corn and 7-19% soybean production yield by 2100.

According to Bebber, Ramotowski, and Gurr (2013), climate change also increases the risk of prevalence of crop pests and livestock diseases that underpin production, for instance, outbreaks and expansions of transboundary pests and diseases of plants and animals (such as coffee leaf rust epidemics in Central America, avian influenza, brucellosis) have severe repercussions on human health and food security.

Also, increasing temperature, increasing concentrations of CO_2, and precipitation variation affect most of the critical factors for livestock production, such as water availability, animal production, reproduction, and health (Rojas-Downing, Nejadhashemi, Harrigan, and Woznicki, 2017). Climate change will also lead to a higher incidence of droughts in many parts of the tropics that significantly impact rainfed smallholder farming systems, particularly in semi-arid regions.

Moreover, the nutritional properties of some crops are expected to be altered due to climate change, especially under conditions of high levels of atmospheric carbon dioxide. For example, a study found that elevated CO_2 reduces the overall concentrations of minerals by 8% (which is lower than usual) and proteins in the tissues of C_3 plants (such as wheat, rice, and soybeans) while increases the total non-structural carbohydrates (mainly starch and sugar), due to the shift in the plant stoichiometry (imbalance on the nutrients) and ionome (mineral nutrient and trace element composition of the plant). In other words, excess atmospheric CO_2 had effects on the chemical composition of plants (Loladze, 2014; FAO, 2015c).

Besides, the increased risk of melting glaciers and decreasing snowcap due to global warming threatens the livelihood of farmers in many parts of the world. For example, farmers in the Indo-Gangetic plain who depend on the Himalayan glacier source for irrigation systems will face water stress in the dry seasons. Moreover, sea-level rise and changes in the hydrological cycle due to global warming threaten coastal cities (Morton, 2007) and aquaculture production in river deltas and estuaries.

In summary, the rising frequency and intensity of extreme weather events such as tropical storms, floods, droughts, heatwaves, and wildfires, could increase the risk of failure for agricultural production systems of the 21st century (IPCC, 2012, 2014), which in turn threatens global food security, including Mexico.

2.2.3 Water scarcity and eutrophication

As agriculture depends on water sources, both quantity and water quality are crucial to food production systems. However, the increasing impact of climate change and demographic pressure could cause water shortages or scarcity in many world regions and reduces soil fertility, which, in turn, affects plant growth. Besides, excessive irrigation in agriculture farms could also cause waterlogging and salinization issues, diminishing soil productivity. Likewise, the excessive use of synthetic fertilizers containing nitrogen and phosphorus, which are not absorbed by the crops, could pollute either the atmosphere or aquatic ecosystems (United Nations Environment Programme [UNEP], 2011; Rabalais *et al.*, 2014).

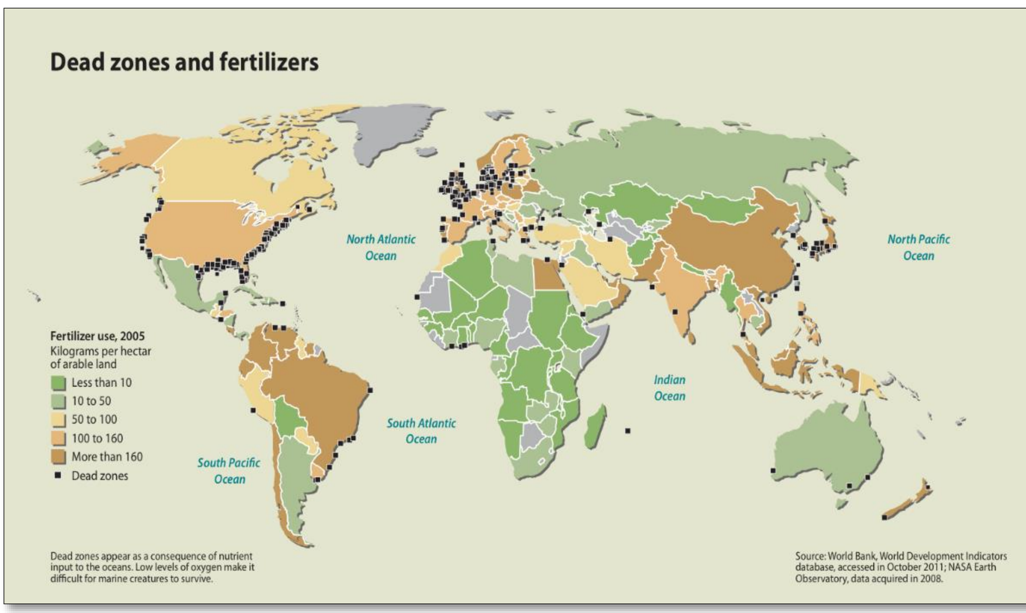

Figure 2. Dead zones and fertilizer use around the world.
(Source: UNEP *et al*., 2012).

To be specific, high nutrient concentrations lead to many algae and microscopic organisms on the surface of water bodies such as lakes. These algal blooms prevent the light penetration and oxygen absorption necessary for underwater life. Also, the dense population of these algae and microorganisms deplete the oxygen content in the water as they die and decay begins. This, in turn, creates low-oxygen or hypoxic conditions (occur when dissolved oxygen concentrations are less than 2mg/L) for aquatic life and cause dead zones or eutrophication, where life could not thrive. For example, the Gulf of Mexico suffers from hypoxia (Figure 2), which threatens the lives of many aquatic organisms, including fish and shrimp. (UNEP *et al.*, 2012; Rabalais and Turner, 2019).

2.2.4 Degradation of land and soil erosion

Agriculture depends on productive land with fertile soil. Soil nutrients are essential to nourish plants. Microscopic organisms within the soil are responsible for most of the nutrient release from organic matter. But the long-term use of high amounts of synthetic inputs in the agricultural plots increases soil acidity, which impedes plant growth and reduces biomass production. Also, high doses of pesticides in the long term make crops more vulnerable to pests and diseases. In some cases, the degraded land will turn into a deserted or unproductive area and reduce the land available for agriculture (Ramankutty *et al.*, 2018).

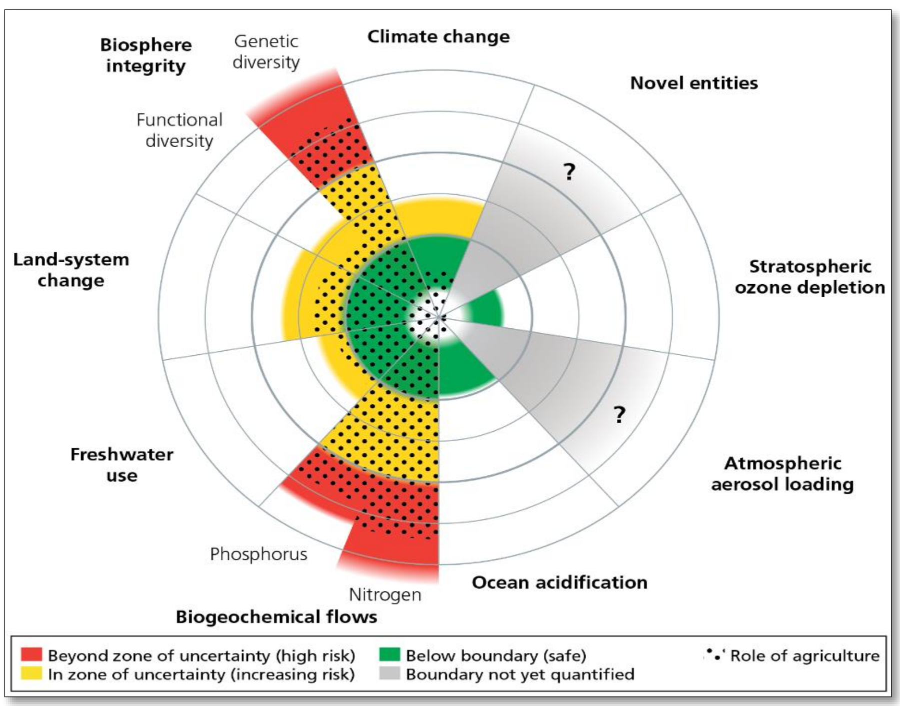

Figure 3. The status of the nine planetary boundaries overlaid with estimates of agriculture's role in that status.

(Source: Campbell *et al.*, 2017).

A study by Campbell *et al.* (2017) concludes that agriculture's role in the status of the nine planetary boundaries - based on the modification for freshwater use from below safe limit (Steffen *et al.*, 2015), into a zone of uncertainty (Gerten *et al.*, 2013; Jaramillo and Destouni, 2015), and an estimate for functional diversity (Newbold *et al.*, 2016) - indicates that agricultural activities play a critical role in determining the Earth's overall sustainability (Figure 3).

Extreme poverty is a multidimensional concept that refers to the people who cannot meet their basic human needs -such as food, water, sanitation, shelter, safe energy, education, and access to other essential services like health care or transport- and struggle even for their survival (Sustainable Development Solutions Network [SDSN], 2012; Sachs, 2015). Globally, about half of the world population (4.75 billion people) suffer from moderate to extreme poverty, and more than 1.2 billion people are living in extreme poverty with an income below a poverty line of US $1.90 per day. And the highest proportions of extreme poverty are still found in tropical Africa and South Asia, primarily concentrated in rural areas (World Bank, 2016).

However, the persistence of extreme poverty in a country or region depends on many factors such as lack of natural resources, infrastructure, technology, education, social protection systems, favorable geographical patterns, environmental and agricultural policies to achieve economic growth etcetera.

2.3 The global state of socioeconomic and cultural challenges

Many socio-economic and cultural challenges (such as extreme poverty, food insecurity, increasing global population, urbanization, massive migration, erosion of traditional knowledge) not only threaten the livelihood of millions of people but generate a vicious cycle that influences farmers decisions regarding the management, use, and conservation of agroecosystems, including homegardens.

2.3.1 Extreme poverty

According to the World Bank (2016), reducing extreme poverty rates by 2030 will not be achieved without lowering inequality between rural and urban areas, regions, ethnic groups, men, and women. Inequality increases the gap between rich and poor. Besides, poor health conditions, lack of essential services, unemployment, lack of sufficient food, and income could impede an individual from escaping the vicious cycle of poverty. Moreover, achieving global food security and nutrition is impossible without addressing the challenges involved in all dimensions of poverty and hunger at different scales.

2.3.2 Food insecurity and malnutrition

Food security includes access to nutritious food by all people. There exist numerous definitions of food security. However, many of these definitions acknowledge the multifaceted concept of food security and highlight four broad dimensions: food availability, accessibility and adequacy/utilization, and stability (FAO, 1996; FAO, 2008a & 2008b; Galhena *et al*., 2013).

Despite the breakthroughs achieved in food productivity based on scientific advances (e.g., the green revolution of high-yield crop varieties that took off in the 1960s) and technological progress (e.g., efficient energy cum fertilizer inputs), as well as the implementation of numerous instruments and kinds of policies (e.g., zero hunger), combating food insecurity and malnutrition remains one of the most fundamental and complicated unresolved challenges facing humanity in the 21st century (FAO, 2008a, 2018).

Recent estimations indicate that more than 820 million people worldwide are chronically hungry or malnourished, i.e., insufficient intake or lack of energy in calories and proteins, which is a rising global hunger level, compared to the 804 million in the world year 2016. Besides, about 151 million children under five years of age suffered from stunted growth, i.e., a low height for their age), while 50 million suffer from wasting, i.e., a low weight-for-height ratio (FAO, 2017c, 2018).

According to Sachs (2015), more than one billion people suffer from hidden hunger (one or more micronutrient deficiencies), and about one billion people are obese (excessive intake of calories). In total, around 3 billion out of 7.2 billion people, i.e., approximately 40% of the world population, suffer from one or another kind of malnutrition, and millions of people die from this cause. Furthermore, the latest available data from the Global Hunger Index (GHI) 2018 report shows that approximately 124 million people suffer acute hunger worldwide. Also, levels of need are alarming in more than 51 countries and highly alarming in one country (Figure 4).

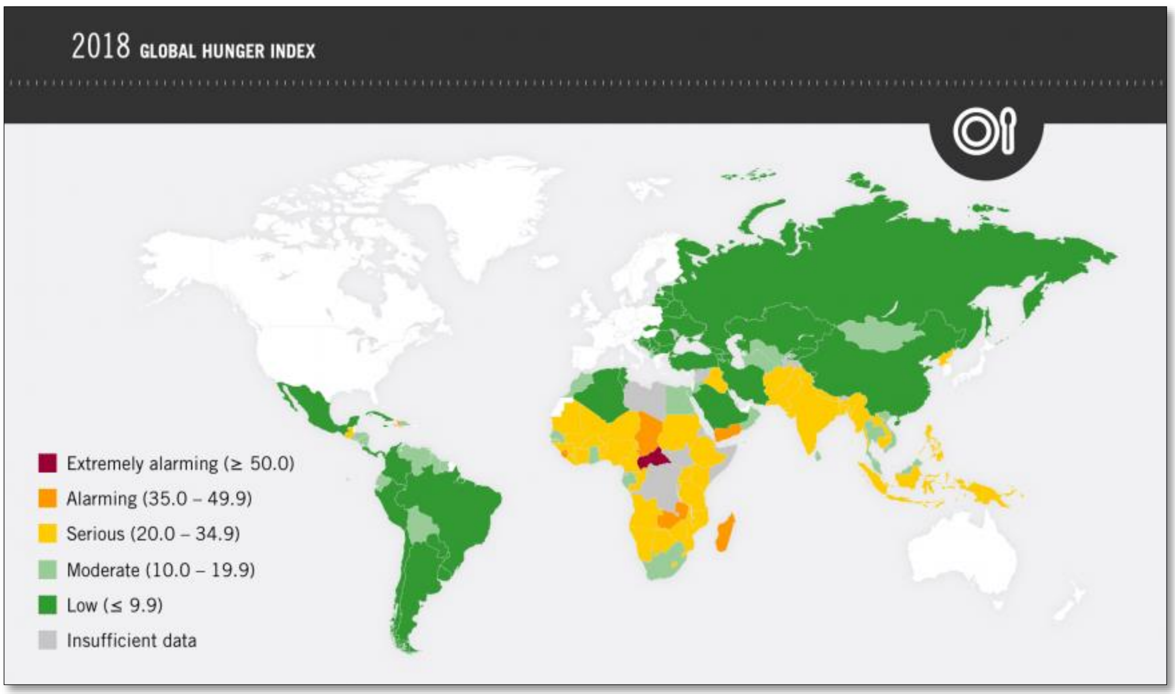

Figure 4. Global Hunger Index 2018.

(Source: GHI, 2018).

In the case of Mexico, despite national strategies such as the Crusade Against Hunger, both poverty and food insecurity remain persistent mainly due to a lack of efficient political structural processes and public policy to guarantee the democratic control of the nation's agro-food system (FAO, 2015a; Lemos Figueroa, Baca del Moral, and Cuevas Reyes, 2018). As a result, more than 55.3

million (46.2%) people are living in a state of poverty, and about 28 million (23.4%) people have deficient access to food, of which the majority lives in rural landscapes (*Consejo Nacional de Evaluación de la Política de Desarrollo Social* [CONEVAL], 2015). Also, more than 69.5 % (i.e., 8.4 million) of the indigenous people in Mexico live in poverty, of which 3.4 million face extreme conditions (CONEVAL, 2019).

Currently, ending hunger and attaining global food security is one of the Sustainable Development Goals' priorities in the 2030 agenda (United Nations [UN], 2015). According to FAO estimates (2018), an average daily caloric availability per person would be 3,130 kcal per day by 2050. However, attaining these goals remains doubtful. Moreover, the global food insecurity problem worsens with the continuous need to satisfy the demands of a growing human population and adverse environmental changes such as climate change threatening the current and future food production systems.

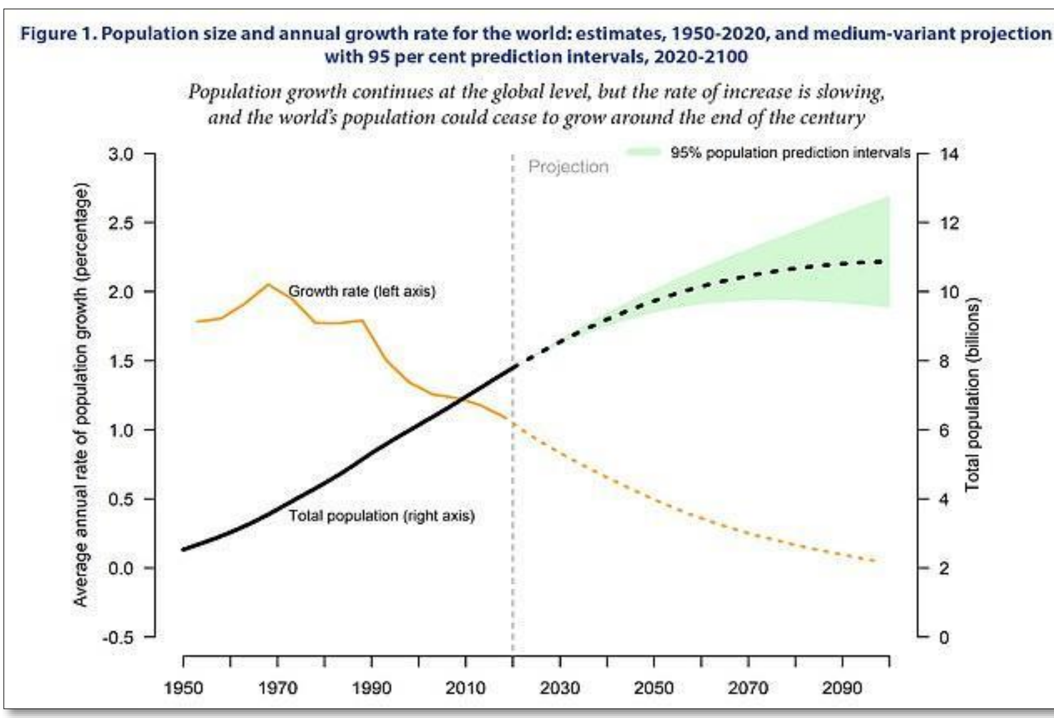

Figure 5. Population growth dynamics to 2100.

(Source: UN-DESA, 2019).

In summary, as many global environmental and socio-economic challenges are intertwined, the impact and feedback influence each other too. For instance, food price fluctuations and increasing volatility significantly impede access to enough nutritious food for the millions of people who live in extreme poverty, which in turn creates a vicious circle of poverty, hunger, and food insecurity (Lemos Figueroa *et al.*, 2018). Besides, the above global trends regarding the dimension of food poverty are disappointing. They indicate both the need for building the resilience of food and agricultural systems and more efficient government interventions at different scales.

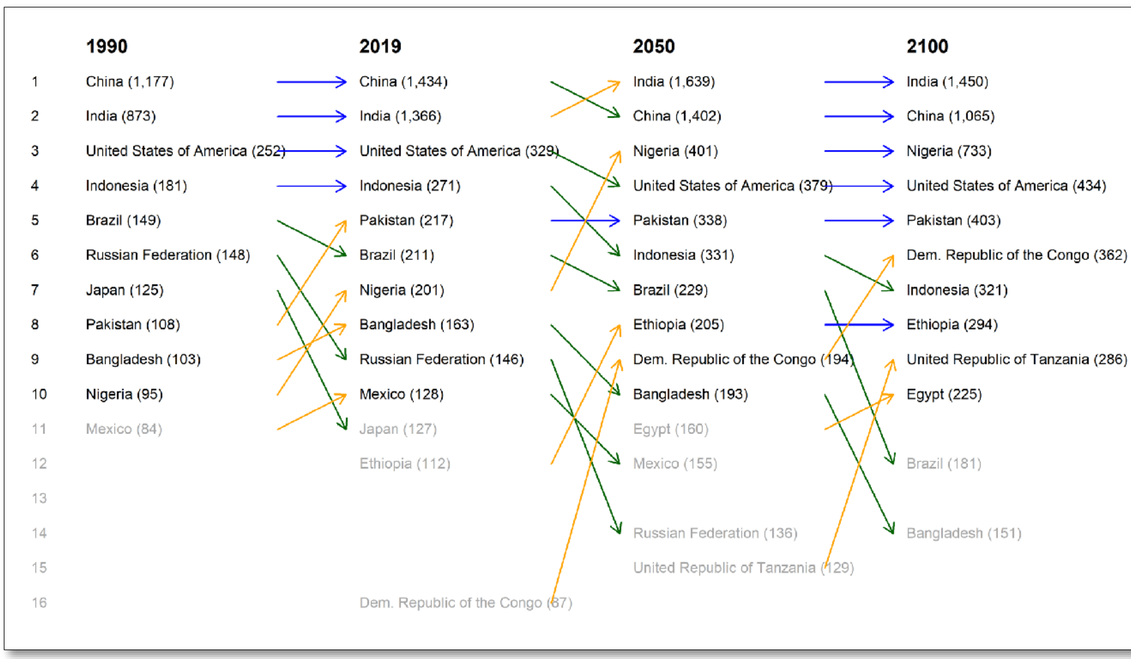

Figure 6. Estimation of high concentration of population in the top ten countries from 1900-2100

(Source: UN-DESA, 2019).

2.3.3 Global population dynamics

Major global population dynamics such as population growth, population aging, migration, and urbanization are destructive driving forces that have crucial implications for sustainable development, especially food security and nutrition. Throughout human history, the world population rate changed very little until the

Industrial Revolution in 1750. However, since 1798, the world's population has increased from 900 million to more than 7.7 billion people at present. According to the United Nations Department of Economic and Social Affairs (UN-DESA, 2019), the projection of the medium-variant scenario indicates that the global population could grow to around 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion by the end of the century (Figure 5).

Latin America and the Caribbean population have tripled in size between 1950 and 2019 and is expected to reach about 768 million around 2058. Besides, more than half of the projected increase in the global population to 2050 will be concentrated in just nine countries (Figure 6), namely India, China, Nigeria, United States of America, Pakistan, Indonesia, Brazil, Ethiopia, and the Democratic Republic of the Congo. In addition, around 47 least developed countries designated by the United Nations are also expected to remain at a high population growth rate (UN-DESA, 2015, 2019).

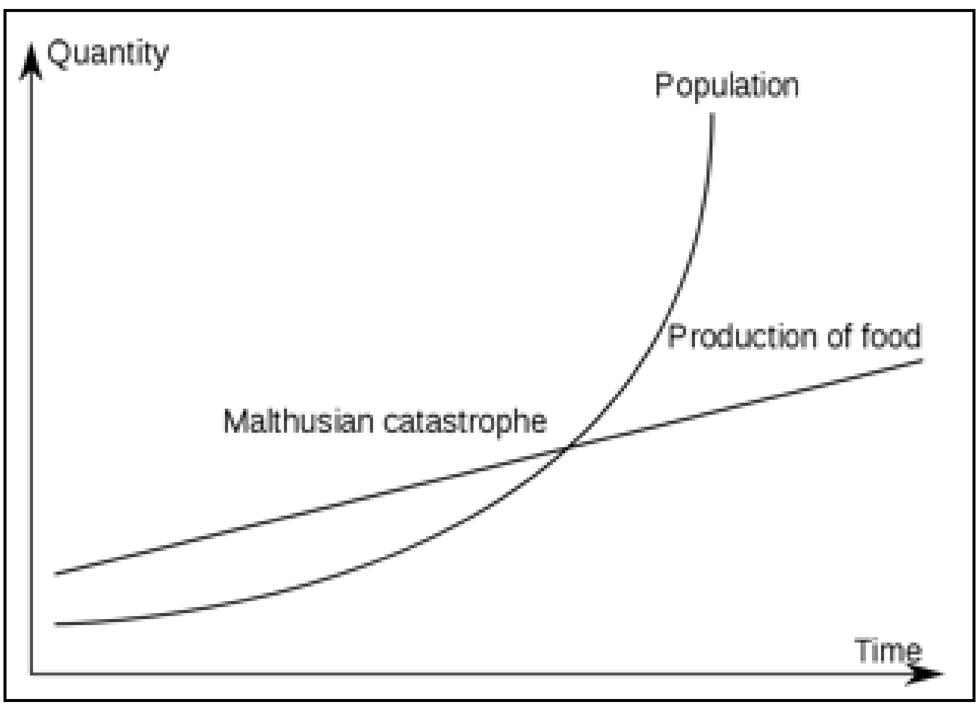

Figure 7. Malthusian catastrophe.

(Source: Malthus, 1798).

The famous economist Thomas Robert Malthus, in his work "An Essay on the Principle of Population" (1798), argued that the population rate grows faster (geometric progression) than the amount of food supply (arithmetic progression). Also, he warned that at some point, the food production would not meet the global demand of the increasing population, and the world would face catastrophes such as conflicts and wars for natural resources. In other words, as the population on the planet increases, the pressure on natural resources is also rising and will accelerate in pace and intensity worldwide (Figure 7). For instance, to feed the expected growing global population, approximately 9 billion, in 2050, it has been estimated that food and biofuel production will need to rise to 50% above 2012 levels (FAO, 2017a). For that reason, Sarukhán (2013) considered Malthus as one of Darwin’s muses (*musas*), and named as the one with the cleft lip (*la del labio leporino*).

Considering the current global trends and the prediction of the Malthusian catastrophe, the world population may be reaching the point of hitting food resource constraints with dire consequences at different scales. In that case, the major challenge will be how to achieve a food supply that provides all the nutrients and the energy needs of the high population worldwide without degrading the natural resources and trespassing the planetary boundaries.

2.3.4 Urbanization and Migration

Urbanization and migration from rural to urban areas significantly impact food security and nutrition in many ways. Land-use change, deforestation, and habitat fragmentation to develop urban areas and infrastructure lead to agrobiodiversity loss, affecting food security at different scales and households. In recent years, people living in cities have increased.

Back in the 1960s, more than 60% of the global population lived in rural areas. However, more than half of them, i.e., about 54%, now live-in urban cities. Projections indicate that more than two-thirds of the population will be living in urban areas by the year 2050 (Figure 8). Also, many urban middle-class people's food preferences will change towards processed food, meat, and dairy products (UN-DESA, 2015; FAO, 2017a).

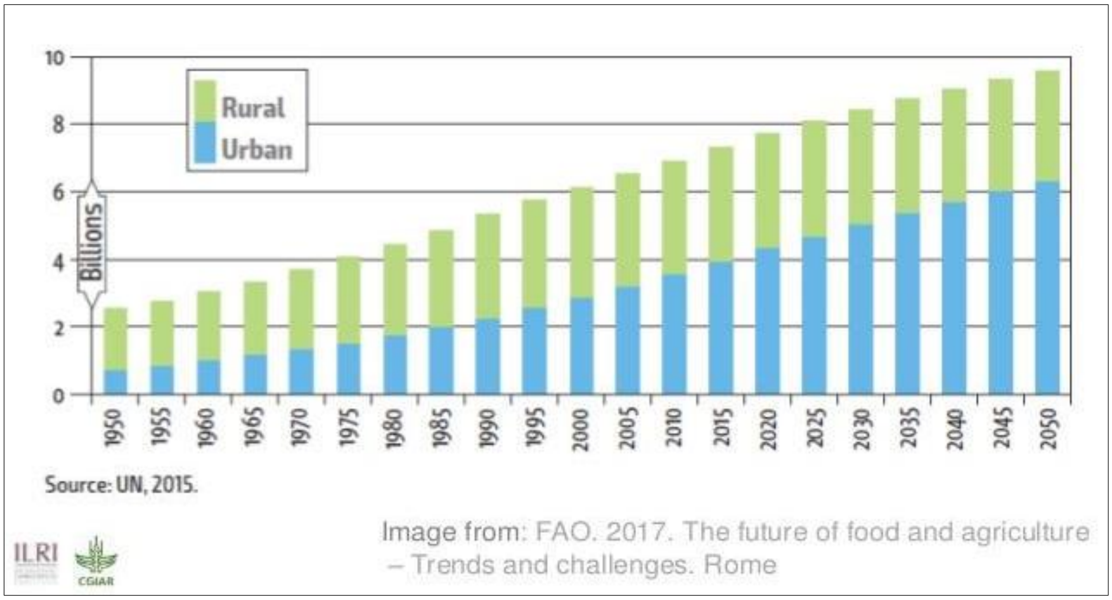

Figure 8. Growth in global urban and rural populations to 2050.

(Source: UN-DESA, 2015; FAO, 2017a).

Migration refers to the movement of people to neighboring towns or countries in pursuit of economic stability and social security. Lack of access to land or other natural resources, secure incomes in the agricultural sector, food security, and employment opportunities are primary causes for rural migration. Although migration brings some options for the place of origin, it also brings lots of challenges. For example, it provides additional cash flow through remittances and narrows the gender gap in agriculture. However, the rural depopulation rate primarily affects agricultural production patterns in rural areas due to the lack of a labor force. As a result, it increases the work burden to those left behind, especially women and aging people. In addition, conflicts, wars, and natural hazards also cause significant displacement or migration of the population (FAO; 2017a, 2017c).

Also, extreme weather events or civil disputes could disrupt food production systems by causing severe physical damage and monetary loss, forcing millions of people to migrate to search for better opportunities or security. Increasing migration combined with the growing population adds pressure on natural resources in destination countries. It creates new conflicts by reinforcing the vicious cycle of population and resource pressure, food insecurity, and poverty (FAO, 2017a).

2.3.5 Erosion of traditional knowledge

Globally, the extinction of biological and cultural diversity, coupled with cultural erosion due to modernization, migration, and occupation changes due to economic pressures that threaten the loss of traditional ecological knowledge (TEK), is one of the current challenges. For example, according to UNESCO (2003), up to 90% of languages will be extinct or threatened by 2100, and thereby, traditional knowledge associated with these languages will disappear.

Likewise, according to FAO (2019), since the 1900s, three-quarters of all crop genetic resources were lost (i.e., within the past 100 years) due to different environmental, socioeconomic, and cultural challenges such as human-induced climate change, the shift in food preferences, land-use change, lack of protection of traditional varieties, lack of appreciation to natural resources, generational gap etcetera.

Benz, Cevallos, Santana, Rosales, and Graf (2000) indicate that the traditional knowledge about plants suffered a decline that accompanied the loss of the indigenous language in some communities in the Sierra de Manantlan of western Mexico. Also, the author concludes that this erosion of knowledge in those communities was mainly due to the notable effects of the modernization process, such as the quality of housing and literacy. Therefore, safeguarding knowledge associated with biological and cultural diversity becomes a priority in the global plan to contribute to the well-being of society.

2.4 Homegardens as a strategy to contribute to a sustainable future through Multifunctional Agriculture

As agricultural activities have a significant impact on Earth systems, consequently triggering the planetary boundaries and threatening the livelihood of millions of species, it is essential to focus on a new model of agriculture that contributes to building a sustainable era for all. Thus, the following sub-sections explore the potential role of multifunctional homegarden agroecosystems as a strategy to contribute to sustainable development.

2.4.1 Evolution of sustainable development concept

The first United Nations (UN) Conference on Human Environment in Stockholm in 1972 has first brought global attention to the challenge of maintaining sustainability while attaining economic growth and development (UN, 1972). That same year, the book "The Limits to Growth" published by the Club of Rome, correctly pointed out that unless drastic changes are made very soon to stop the continual growth in population and production without considering the limits of Earth's finite resources, our social and economic system will collapse, possibly within as little as 70 years (Meadows, Meadow, Randers, and Behrens, 1972). This study of the future caused shock waves and concern among the international community of scientists, environmentalists, and policymakers.

Later, the authors of the publication entitled “World Conservation Strategy: Living Resource Conservation for Sustainable Development” argued that human beings must consider the reality of resource limitation and the carrying capacity of the ecosystems during the process of economic development. The primary purpose of this document was to help advance the achievement of sustainable development through the conservation of living resources (International Union for Conservation of Nature and Natural Resource [IUCN], United Nations Environment Program [UNEP], and World Wildlife Fund [WWF], 1980).

In 1982, the term sustainable development was adopted and popularized in the report generally known as the Brundtland Commission, presented by the chairwoman Gro Harlem Brundtland of the United Nations Commission on Environment and Development. According to Brundtland (1987), the classic definition of sustainable development relates to the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Figure 9. Sustainable development goals of the 2030 agenda.

(Source: UN, 2015).

The Rio Earth Summit in 1992 also emphasized the intergenerational concept of sustainable development. And it was declared as a fundamental principle, i.e., development today must not threaten the needs of present and future generations. Later, at the UN World Summit on Sustainable Development (WSSD) in Johannesburg in 2002, the intergenerational concept of sustainable development evolved into a holistic developmental approach that integrated three components- environmental protection, economic and social development - as interdependent and mutually reinforcing pillars of sustainable development (WSSD, 2003). Finally, scientists and developmental strategists again emphasized the three dimensions (environmental sustainability, economic development, and social inclusion) of sustainable development on the twentieth anniversary of the Rio summit, i.e., during the Rio+20 Summit ("The Future We Want") by the year 2012 (UN, 2012).

The call for the world leaders to create a new global agenda of Sustainable Development Goals (SDG) in "The Future We Want" was implemented by the UN Sustainable Development Solutions Network (UN-SDSN), which proposed ten SDGs, each one with three associated specific targets as well as more than ten numerical indicators to track progress on the goals and targets (Sachs, 2015). Later, the adopted resolution of “Transforming our World: the 2030 Agenda for Sustainable development” was a plan of action for people, planet, and prosperity which established 17 Sustainable Development Goals (Figure 9) and 169 targets to demonstrate the scale and ambition of this new universal Agenda (UN, 2015).

2.4.2 Towards a new model of agriculture

As mentioned earlier, current challenges such as poverty, food insecurity, malnutrition, and other environmental problems that exist very severely in different parts of the world, particularly in developing countries, require immediate attention. In recent years, faced with these urgent needs, scientists and developmental strategists began to seek a new model of agriculture at different scales (global, national, regional, and local) to mitigate adverse environmental effects and at the same time to meet current demands without compromising the needs of future generations to achieve sustainable development.

To be specific, due to the increased awareness about these adverse effects (on environment and society) of intensive and high-input agricultural practices in the 1970 and 1980s, the concept of multifunctionality of agriculture (concerning food security and sustainable development) got global attention. And during the

“Agenda 21”, FAO (Food and Agricultural Organization) and other institutions focused their attention on new aspects of agriculture that would allow addressing issues such as food security, productivity, and sustainability in the future, and crystallized these ideas in the concept of "Sustainable Agriculture and Rural Development" (SARD), which proposes to promote sustainable development (in the agricultural, fishing and forestry sectors) to conserve land, water, plant, and animal genetic resources, (without degrading the environment), doing so technically appropriate, economically viable and socially acceptable (UN, 1992; FAO, 1999).

2.4.3 Multifunctional Agriculture

The concept of the multifunctional character of agriculture and land (MFCAL) derived from SARD (Sustainable Agriculture and Rural Development) and constituted the new paradigm founded on the notion that all agricultural systems are intrinsically multifunctional, encompassing the full range of environmental, economic, and social functions associated with agriculture and the corresponding use of land. The analysis of this multifunctional character helps to understand the combination of synergies and balances necessary to achieve sustainability in agricultural and rural development (FAO, 1999; Organization for Economic Co-Operation and Development [OECD], 2011).

In this sense, this concept represents a way of analyzing the activity from a more comprehensive perspective since it contemplates the totality of products, services, and externalities that agriculture provides in a given space, which has an either direct or indirect impact on the economy, environment and society (Aldington, 1998; Jessel, 2006, Van Huylenbroeck, Vandermeulen, Mettepenningen, and Verspecht, 2007; Kopeva, Peneva, and Madjarova, 2010).

In general, according to Beverly, Herren, Wakhungu, Judi, and Watson (2009), the concept of multifunctionality refers to agriculture as a multi-productive activity. It produces primary products such as food, feed, fibers, biofuels, medicinal and ornamental plants, environmental, landscape, and cultural heritage services. And for this reason, it is proposed that the management or design of agricultural policy should be aimed at achieving an optimal balance between social, environmental, and economic objectives (Figure 10).

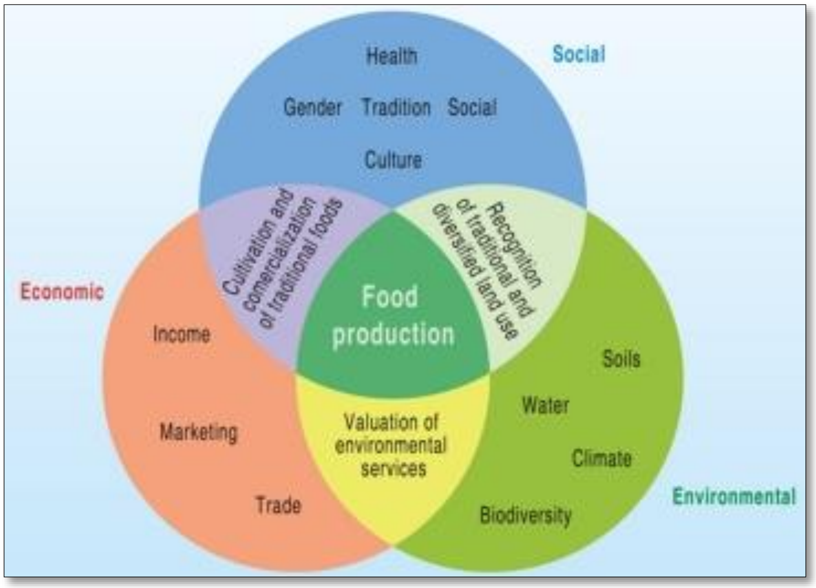

Figure 10. The different roles and functions of agriculture.

(Source: Beverly *et al*., 2009).

2.5 Promotion of traditional agroecosystems for sustainable livelihoods

One of the interests of international development strategists is to achieve sustainable agriculture by strengthening and improving local production systems, which are vulnerable to the adverse effects determined by global phenomena (such as climate change, food insecurity) that have increased recently (IYFF, 2014; FAO, 2017c; FAO, 2018). Consequently, in 2014, FAO celebrated the "International Year of Family Farming" (IYFF, 2014), intending to increase its visibility by focusing global attention on its scope to enhance socio-economic, environmental, and cultural conditions. The goal was to reposition family farming and small-scale farming at the center of agricultural, ecological, and social policies on national agendas, identifying gaps and opportunities to promote more equitable and balanced development, particularly in rural areas.

The concept of family farming coined by FAO has the following definition: "Family farming (including all family-based farming activities) is a way of organizing agriculture, livestock, forestry, fishing, aquaculture, and grazing, which it is managed and operated by a family and, above all, it depends predominantly on family work, both for women and men" (FAO, 2013).

Family farming currently represents more than 80% of the agricultural production in Latin America and the Caribbean, providing between 27% and 67% of the global food production; it also occupies between 12% and 67% of the agricultural area and generates between 57% and 77% of agricultural employment in the region (FAO-BID, 2007). For example, in Mexico, of 5.3 million rural economic units, 3.85 million (representing 73% of the total existing units in the country) are considered subsistence farming units (*Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca* [SAGARPA] and FAO, 2012, 2013).

Likewise, in rural areas, homegardens represent the primary system of family agriculture which is predominantly practiced by indigenous populations (Mariaca, 2012). The agroecosystems of homegardens are examples of multi-functional agriculture because, apart from the provision of food and raw materials, they also provide other environmental goods and services such as the conservation of biodiversity, the regulation of the water cycle, the capture of carbon dioxide, the prevention of erosion, among others. Besides, homegardens enable transmitting knowledge about plant resources generation by generation over centuries (Montagnini, 2006; Mohri *et al.*, 2013; Krishnamurthy, Krishnamurhy, Rajagopal, and Peralta, 2017).

2.5.1 The potential role of homegardens for sustainable development

Globally, homegarden (HG) is a widespread land-use practice (Galhena *et al.*, 2013; Rajagopal *et al*., 2021) and a prevalent subsistence agricultural system in the tropical parts of America (Mariaca, 2012). These systems are well adapted to the local environmental and socio-cultural conditions and transmitted from generation to generation by many indigenous people in rural parts of Mexico (Caballero, 1992; Mariaca, 2012). Like González (2018) and Trabanino (2018), some authors have suggested that it was in homegardens where agriculture was born about 10,000-12,000 years ago. Therefore, it is also considered the oldest land-use activity that has evolved through gradual intensification by generations (Kumar and Nair, 2006).

The general conception of homegarden is a combination of trees and crops forming different floors, sometimes associated with domestic animals around the home (Fernandes and Nair, 1986; Soemarwoto, 1987; Torquebiau, 1992). Within agroforestry systems, homegardens occupy a significant place. No other system is so diverse regarding the number of species, varied in its structure and possible associations and complex functions (Lok, 1998; Kumar and Nair, 2004).

HGs also represent the multifunctional agriculture due to the presence of species of different functional groups such as food crops, vegetables, fruit trees, medicinal plants, spices and condiments, drinks, ornamental plants, as well as domestic and wild animals (Wiersum, 1982; Fernandes and Nair, 1986; Niñez, 1987; Soemarwoto, 1987; Kumar and Nair, 2004; Krishnamurthy *et al.,* 2017). Mariaca (2012) considers homegardens as the complex agroecosystem, and it is the family that shapes and determines its extension, structure, form, and function. These systems are recognized as the largest plant and animal food for rural families and act as an actual agrobiodiversity reservoir.

Moreover, it is highly considered a local food system in which the people could produce, distribute, and consume food. Also, it permits control of the mechanisms and policies of food production and distribution. Thus, it is contrary to the food regime in which corporations and market institutions dominate the global food system.

In other words, the homegarden system helps to achieve food sovereignty, i.e., a political exercise of self-determination, autonomy, vindication, and sustainability

(Carballo, 2011; Rajagopal *et al*., 2021). Thereby contributing to achieving the four dimensions (food availability, accessibility, utilization, and stability) of food and nutritional security at individual, family, and community levels. Consequently, it contributes to sustainability, particularly for bottom-up development (Quisumbing, Brown, Feldstein, Haddad, and Peña, 1995). Data evidence worldwide suggests that homegardens provide an essential mechanism for addressing food insecurity in different challenging situations (Galhena *et al.*, 2013; Rajagopal *et al*., 2021). For instance, homegardens can give food to resource-poor communities within a small patch of land with limited or no additional inputs (Mitchell and Hanstad, 2004).

Indeed, households in the poorest and most remote communities of Cuba (Buchmann, 2009), Indonesia (Wiersum, 2006), and Tajikistan (Rowe, 2009) have depended on homegardens as a reliable and convenient source of food. According to García-Flores, Gutiérrez-Cedillo, Balderas-Plata, and Araújo-Santana (2016), family vegetable gardens constitute a livelihood strategy for smallholder farming families in Mexico. Also, it fulfills the needs of the family diet and strengthens socio-environmental resilience and sustainability.

Several other studies on homegardens have focused on its structural complexity (Soemarwoto, 1987), structure and function (Fernandes and Nair, 1986), biodiversity, food security and nutrient management (Montagnini, 2006; Cahuich - Campos, 2012), economic gains (Mohan, Alavalapati, and Nair, 2006; Cámara-Córdoba, 2012); the problems of sustainability (Torquebiau, 1992; Torquebiau and Penot, 2006). However, evidence from several research reports indicates that home gardens can be a sustainable strategy to improve food security and income when they have well adapted agronomically to the conditions of local resources, traditions, and cultural preferences (Midmore, Niñez, and Venkataraman, 1991; International Institute of Rural Reconstruction [IIRR], 1991; Krishnamurthy and Krishnamurthy, 2016; Krishnamurthy *et al.*, 2017; Rajagopal *et al*., 2021).

In summary, with the year-round production of various nutritious food being the primary purpose, homegardens also offer multiple other products and services such as traditional medicine. And therefore, it represents the multifunctional land-use systems that not only provide food but also conserve biodiversity, contributes to gender equality, social justice, value indigenous wisdom, and preserve cultural heritage (Pimbert, 1999; Nair and Kumar, 2006; Beverly *et al*., 2009, OECD, 2011; Rajagopal *et al*., 2021).

Moreover, these homegardens have existed since immemorial times indicate that its associated agrodiversity contributes to family food sovereignty. Also, its management strategy based on recycling facilitates sustainable resource use. Thus, homegardens may represent a pathway toward food sovereignty in rural, urban, and suburban areas (Cano Contreras, 2015) and contribute to achieving sustainable livelihoods.

2.6 General concepts relevant to the current research

2.6.1 Biocultural heritage

Many indigenous people worldwide (about 370 million) rely on biocultural heritage (BCH) for survival. The origin of this concept can be traced back to the 1980s, as well as the emerging interest in the conservation of biological resources, local knowledge, land-use practices, and heritage values that define sustainability and resilience from the perspective of local inhabitants (Maffi and Woodley, 2012; Ekblom, Shoemaker, Gillson, Lane, and Lindholm, 2019). Mainly from the adoption of the *Convention on Biological Diversity* (CBD) from 1992 at the Earth Summit in Rio de Janeiro, as well as the adoption of the Nagoya Protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization (ABS) in 2010 influenced in the evolution of the concept of BCH.

The United Nations Educational, Scientific and Cultural Organization (UNESCO) uses the term “biological cultural heritage” to refer to ecosystems (including habitats and species) originating or developing from human practices (UNESCO, 2008 & 2014). In general, the concept of BCH refers to the inter-linked biological and cultural diversity of indigenous peoples and local communities, from seeds to landscapes and from knowledge to spiritual values, handed down from generation to generation (International Institute for Environment and Development [IIED], 2005; Krystyna, 2017).

In other words, it is centered on the relationship between indigenous people and their natural environment. And its components (i.e., biological resources and traditional knowledge) are inextricably linked to traditional resources and territories, local economies, the diversity of genes, species and ecosystems, cultural and spiritual values, and customary laws shaped within the socio-ecological context of communities (Figure 11).

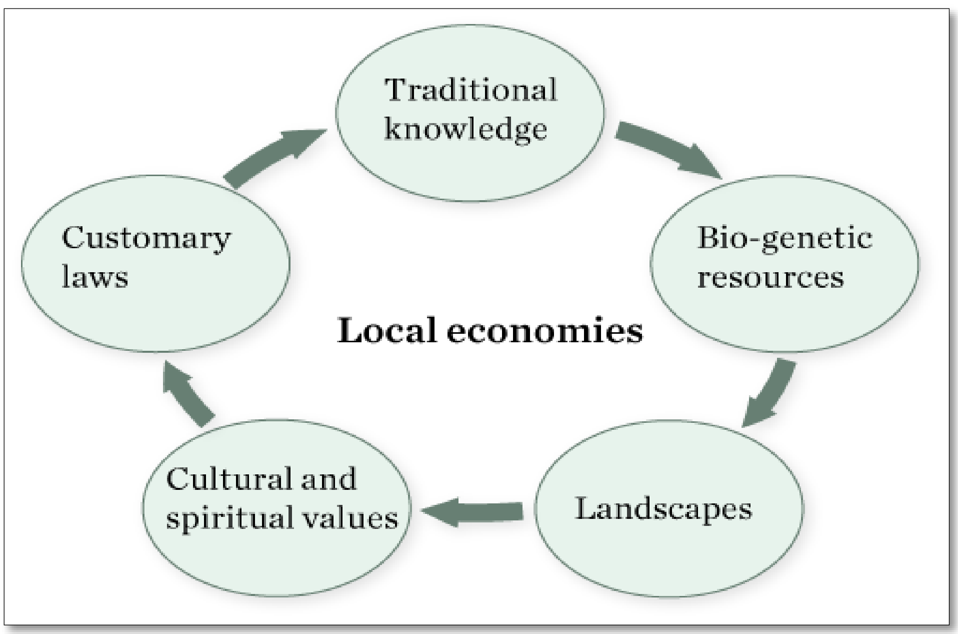

Figure 11. The concept of biocultural heritage.

(Source: IIED, 2005).

According to Alcorn (1997), the knowledge of the native people is often expressed through mute language, which is reflected in their attitudes towards the environment and their way of living. Cuevas (2019) indicates that the best way to inherit this knowledge to the future generation is by the example, representing through the course of living. Also, he emphasizes that the culture could not be conserved like the germplasm of plants in a cold room of gene bank.

Biocultural heritage in Mexico

Mexico is not only recognized as one of the 12 mega diversity nations in the world, but it also encompasses 22 biocultural regions (indigenous territories) with high biodiversity levels (such as centers of domestication of species and landscapes). For instance, the accumulation of knowledge relevant to plant resources (such as food, medicine, fiber) is part of the biocultural heritage, which is still reflected in the cultural and spiritual values of the native people in the country (Boege, 2008, Villamar, 2013).

According to Cuevas (1991), “plant resources (RV) are the result of the existing correlations (Figure 12) between the amplitudes and limitations of the ecological environment (ME), the culture inherent to the human species (C), and that part of the vegetation (V) perceived by human groups as a resource over time (T). In short, plant species are appreciated by man as valuable elements of nature and used to satisfy some types of their needs are considered plant resources.

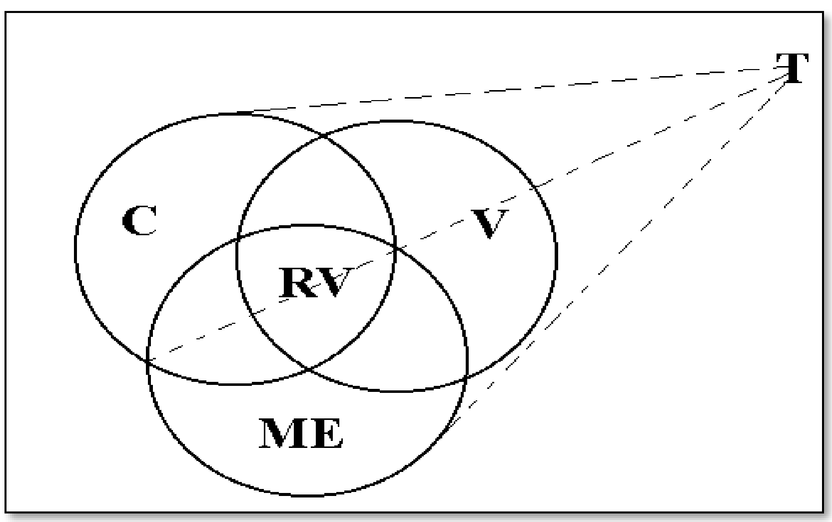

Figure 12. Schematic representation of plant resources.

(Source: Cuevas, 1991).

The knowledge regarding the process of selection, cultivation, and domestication of plants, for example, the creation of maize from the *Teosinte*, the closest wild relative, is part of the biocultural heritage of Mexico due to its antiquity. Indeed, more than 68 races of maize are distinguished by the native people based on their color, size, vigor, and other characteristics. Also, maize has become so overwhelmingly influential in the people's social, cultural, and economic life and central to their identity. Therefore, in general, considering the richness of a nation with 10% of the world's biodiversity and 364 living languages, the protection of biocultural heritage has been included in Mexican law on Ecological Equilibrium and Environmental Protection (IIED, 2020).

2.6.2 Agroecosystems

Traditional agroecosystems or agricultural systems are recognized globally as part of BCH mainly due to the intentional management and conservation of a wide diversity of crops and livestock based on accumulated knowledge and passed down over generations-and sometimes millennia (Boege, 2008). According to Altieri (2009), agroecosystems are an implemented strategy for natural resource management where management, use, and conservation of plants, animals, seeds were carried out based on traditional knowledge, which is closely related to the cosmogony of the communities (Toledo and Barrera-Bassols, 2008; Calvet-Mir *et al.*, 2014). Besides, agroecosystems are integral units in the study of ethnobotany, and to understand their evolution, and it is essential to study the existing interrelations between plants and humans.

More than 70% of the total population in Mexico depends on these traditional agroecosystems such as homegardens, milpa, family agriculture, agroforestry, shifting cultivation, and mixed cropping for their livelihood and nourishment, particularly the indigenous communities of rural landscapes. Moreover, according to Villamar (2013), agricultural centers are correlated with the most important cultural diversity areas, so these areas are constituted as a great wealth of agricultural and cultural resources.

2.6.3 Biological diversity

Biological diversity or biodiversity results from ecological and evolutionary processes and refers to the variety of living beings that inhabit the Earth. There are three types or levels of biodiversity: genetics, species, and ecosystem (Figure 13). Biodiversity provides the genetic basis for all agricultural plants and animals. Besides, it provides ecological benefits that help promote nutrient cycling and energy flow, perpetuates species, provides the genetic basis of farming plants and domestic animals, control microclimate and erosive processes, and regulate synthesis and decomposition. of organic compounds (Altieri and Nicholls, 2000).

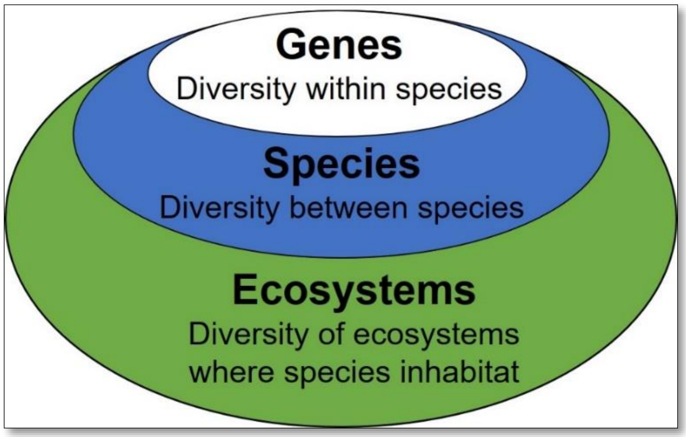

Figure 13. Organization levels of the concept “biodiversity”.

(Source: *Comisión Nacional para el conocimiento y uso de la Biodiversidad* [CONABIO], 2021).

Homegardens, for instance, are modified ecosystems where man replaces natural diversity for the establishment of species of anthropocentric interest. According to Altieri, Nicholls, and Montalba (2014), agroecosystem such as homegardens are distinguished due to the presence of four types of biodiversity: productive (crops and animals), destructive (pests, weeds, diseases), neutral (non-pest herbivores that serve as food predators) and beneficial or functional (pollinators, natural enemies, worms, soil microorganisms, among others), which play ecological roles in pollination processes, biological pest control, nutrient recycling, among others.

The importance of wild plants as potential resources

Wild plant diversity act as a source of new resources. Therefore, determining wild plant's actual and potential utility is essential to move towards a new model of agriculture. According to Pernés (1983), if we want to avoid agronomic catastrophes in the future, we must lovingly preserve both the populations of the wild forms and those of the traditional varieties. Regarding the research about plant resources, less than 2% of studies focus on wild and tolerated species' actual and potential use. In comparison, more than 98% of studies focus on the importance of fomented, cultivated, and domesticated species (Figure 14). However, many modern agricultural systems eliminate the diversity in the natural ecosystems without considering the potential use of the wild plants and promote monoculture to increase monetary gains. In this context, Hernández (1970) questioned the authorities that if you do not know the current or potential usefulness of this group of plants, then what makes you cause their destruction?

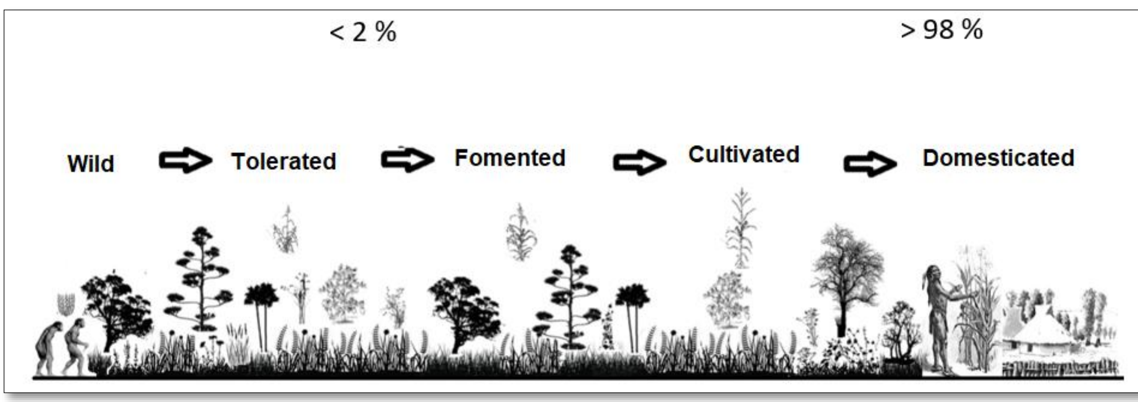

Figure 14. Degree of management of plant species.
(Source: Pernés, 1983).

According to the classification of degree of management, wild plants are those species in which man has not exerted any influence but can give them some use category. Tolerated plants are those species that man has not modified, but that presents some utility within the agroecosystem. Fomented plants refer to the promotion of those individuals of various species through actions to increase the distribution and dispersal of sexual and vegetative propagation of the plants.

Cultivated plants are those species to which man applies cultivation technology to promote better development in their environment. Finally, domesticated plants are those species in which man has exercised a selection of anthropocentric interest characters.

The importance of Etnotaxa

Hernández (1970) recounts that an old farmer in Tlaxcala has grown three different colors of maize in his field. The rationality behind the farmer's decision to plant different varieties (yellow, purple, and white) of maize was because each has a different life cycle (five, six, and seven-month period) and yield performance (less, little more, and better). Growing altogether provides the minimum guarantee of yield, as no one can predict the rain patterns to ensure the yield of a particular variety. Thus, the study of etnotaxa (i.e., cultivar, subspecies, race, forms) is essential to understand the biological, ecological, anthropocentric, and cultural importance of plant genetic diversity.

2.6.4 Agrodiversity

Agrodiversity, in general, is defined as "the many ways in which farmers use the natural diversity of the environment for production, including not only their choice of crops but also their management of land, water and biota as a whole" (Brookfield and Padoch, 1994). According to Almekinders, Fresco, and Struik (1995), agrodiversiy is "the variation resulting from the interaction between factors that determine the agroecosystems." In other words, Brookfield and Stocking (1999) state that agrodiversity is the interaction between plant genetic resources, the abiotic and biotic environments, and management practices. Thus, biophysical, management, agro-bio, and organizational diversity are the four main components of agrodiversity (Figure 15).

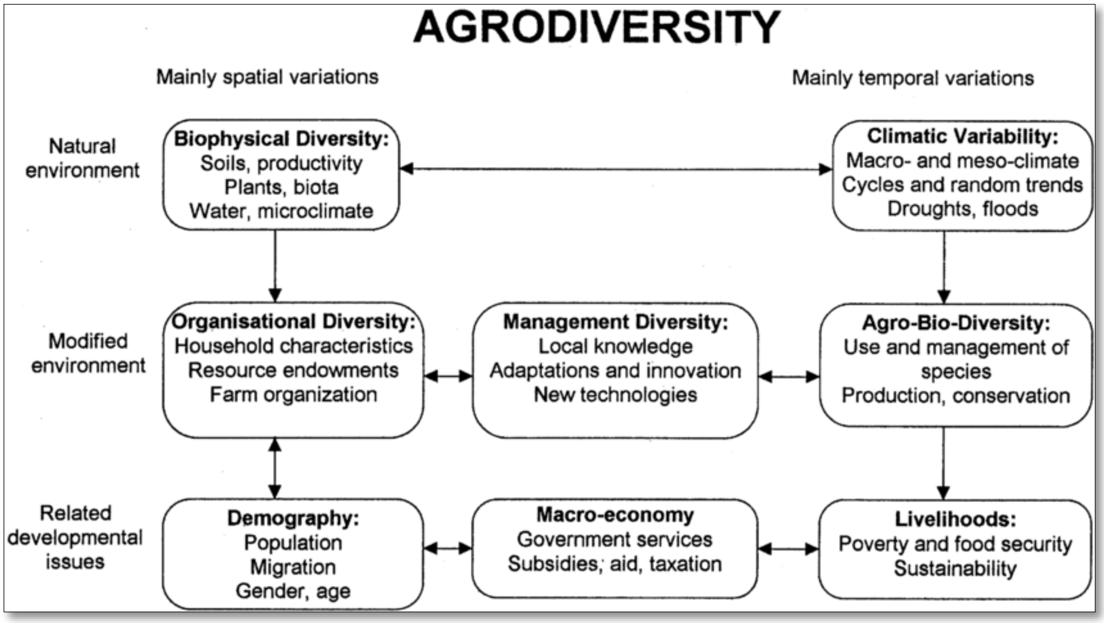

Figure 15. Elements of agrodiversity – main components and principal development issues.

(Source: Brookfield and Stocking, 1999).

Biophysical diversity

Biophysical diversity refers to the variety of the natural environment. The characteristics of biophysical diversity determine the agricultural productivity of a zone influenced by the ecological environment components, including geology, geography, climate, edaphic, vegetation, and animals. However, farmers select and modify this diversity using different management techniques according to their cultural background.

Management diversity

It refers to managing natural resources such as land, water, and biota for food production activities. Many farmers use different management practices to maintain soil fertility, control pests, planning production activities based on seasons or temperature and rainfall patterns, planting hedges or living fences, protecting water by conserving forests, preparing terraces to avoid soil erosion, etc. However, this management diversity is constantly modified based on the knowledge exchange network of the farmers, which varies based on their holistic worldview about nature.

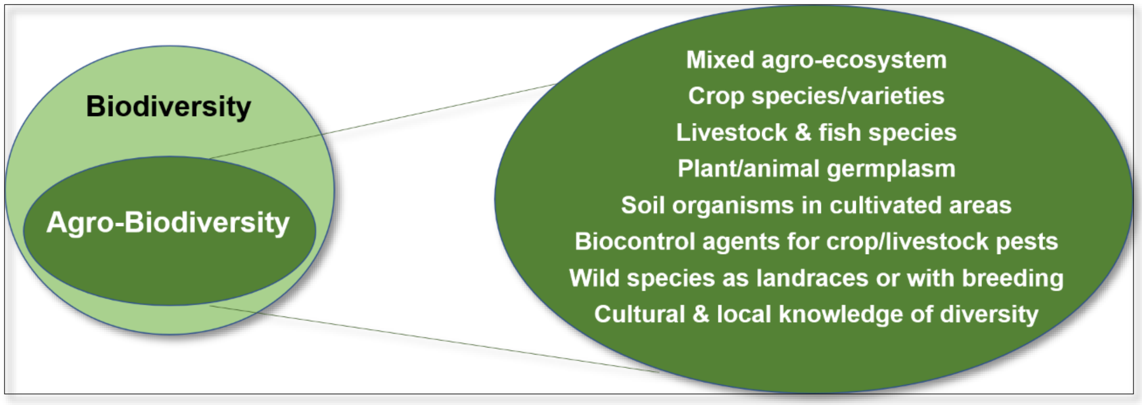

Figure 16. Concept of agrobiodiversity.
(Source: FAO, 1999).

Agrobiodiversity

Agrobiodiversity is the crucial component to sustain the structure, functions, and process of an agroecosystem. In general, it comprises the diversity of animals, plants, and microorganisms involved directly or indirectly to support food and agriculture production (Figure 16).

Furthermore, as local knowledge relevant to plant and animal resources management plays a vital role in conserving biodiversity, cultural aspects are also considered an integral part of agrobiodiversity (FAO, 1999; Zimmerer and De Haan, 2017).

Organizational diversity

It refers to the socio-economic aspects of the management, use, and conservation of natural resource endowment. For instance, labor, family size, market, social cohesion, gender equity, age, policies, institutions, customary laws, access to land significantly influence agrodiversity in a zone.

2.6.5 Cultural diversity

Culture is that complex whole that includes knowledge, beliefs, art, morals, law, customs, and any other capacities and habits acquired by man as a member of society (Tylor, 1871; cited in Carrasco, 1999). In other words, it is the identity of a population that has similar customs, traditions, worldview or ideas, language, spiritual values, and festivals. For example, the indigenous people of Mexico assume an ethnic identity based on their culture, institutions, and history that defines them as the indigenous or native people of the country. CDI (initials in Spanish, stands for *Comisión Nacional para el Desarrollo de Los Pueblos Indígenas*), reports that there are 62 groups of indigenous peoples (ethnolinguistic) living in different ecosystems of Mexico (Navarette, 2008).

Although indigenous people are distributed throughout the nation, they are primarily concentrated in the Sierra Madre del Sur, the Yucatan Peninsula, the most remote or hard-to-reach areas such as the Sierra Madre Oriental, Sierra Madre Occidental, and other neighboring regions (where the indigenous population in Mexico is not numerous) of Mesoamerican cultures.

According to *Instituto Nacional de Lenguas Indígenas* [INALI] (2008), as the country is distributed with approximately 68 ethnic or cultural groups, it is recognized for its richness of biological and cultural diversity. Also, the estimation by the National Indigenous Institute (INI), National Commission for the Development of Indigenous Peoples, the indigenous population in Mexico was approximately 15 million people, divided into more than 56 ethnic groups, who speak between sixty-two to more than hundred different languages (García Valencia, and Romero Redondo, 2009).

Red (2012) and Villamar (2013) argue that the correlation between linguistic diversity and biological diversity appears in the global statistics, where 9 of the 12 main centers of linguistic diversity are also in the registry of biological megadiversity. Reciprocally, nine countries with the highest species richness and endemism are also on the list of nations with the highest endemic languages. However, Cuevas (2019) insists that “there are plants without culture, but not necessarily resources.” Also, the magnitude and the use of plant resources heavily depend on the limitations and amplitudes of the ecological and cultural environment.

2.6.6 The Totonacs

Many indigenous people of Mexico depend mainly on traditional agriculture, particularly family farming, for their livelihood. Totonac is one of Mexico's 68 cultural or ethnic groups and predominates from the Gulf of Mexico to the Sierra Norte de Puebla. Also, they occupied the mountain highlands to the coastal plains, between the *Rio Cazones* and the *Rio Tecolutla*. The etymological interpretation of the term “*Totonaco*” is derived from two words in their language: *tutu* (three) and *naku* (heart), which means three hearts. Some analysts suggest that the term refers to three great ceremonial centers: Tajín, in Papantla, Zempoala near the old foundation of Veracruz, and Yohualichan, in the northern sierra of Puebla. However, the Totonac area has been known as the Totonacapan since the 16th century (Kelly and Palerm, 1952; Harvey and Kelly, 1969).

Totonac language has two main branches called *Totonaco* and *Tepehua*. Pre-Columbian Totonac people were known for their skill in stone carving. *El Tajin* (city of thunder in Totonac language) is one of the critical political and religious places of Totonac located in the north of Veracruz, founded in 4 A.D. and reached its peak between 800 and 1200 A.D. The traditional garment of the Totonac women was the “*quechquémetl*,” which is an embroidered dress, wide and long. The men wore only a loincloth of cotton. The main economic activities are agriculture and commerce. By producing a variety of crops such as corn, cassava, pumpkins, beans, squash, chili peppers, cotton, and liquid amber, Totonac people had immense power among other ethnic groups such as Aztec (Kelly and Palerm, 1952; Harvey and Kelly, 1969; García Valencia and Romero Redondo, 2009).

2.6.7 Traditional knowledge

Traditional or empirical knowledge has been developed by the people who interacted with nature in a particular cultural environment. Therefore, this knowledge is originated independently of science and Western culture. It is defined as the knowledge, innovations, and practices of indigenous and local communities worldwide. In other words, it refers to the system of indigenous knowledge that reflects the holistic worldview about their natural surroundings and cultural or spiritual values associated with their lifestyle (Figueroa, 2013; Villamar, 2013).

This knowledge acquired through experiences adapted to the local culture and environment and transmitted orally from generation to generation. For instance, many world cultures still conserve and convey traditional knowledge through their dance, paintings, sculptures, stories, songs, folklore, proverbs, cultural values, beliefs, rituals, community laws, the local language, and agricultural practices. However, as this collective knowledge is mainly about biocultural memory that includes local biological resources and cultural aspects, today, it is being revalued as a “resource for sustainable development” (Figueroa, 2013; Villamar, 2013).

The relevance of traditional knowledge in the current research is associated with farmers' perception of management, use, and conservation of natural resources, which is reflected in the agroecosystems such as homegardens. Hernández (2007) refers to traditional land-use practices as the technology that has originated in the empirical knowledge of native people, accumulated during twelve thousand years, i.e., from the advent of agriculture, particularly in Mexico. It contradicts modern agricultural practices (e.g., science and technology of the Green revolution) of Western or North American culture. The minimum influence or impact of traditional land-use methods in environmental, economic, and socio-cultural dimensions of multifunctional agriculture for sustainable development determines the importance of farmer's knowledge.

2.6.8 Ethnobotany

Ethnobotany is a scientific branch dedicated to studying the correlation of man and plant involved in agroecosystems' natural and social dynamic. This concept refers to the total functions played by the plants in culture. Therefore, ethnobotanical research text should cover all aspects of the use and management of vegetation in a human community. The fundamental objectives of ethnobotany are 1. Provide information relevant to the use and management of plants; 2. Elucidate ethnobotanical text by defining, describing, and investigating the role or functions associated with the process.

The above objectives are based on the following goals of the ethnobotanical research: generating new products derived from plants, facilitating new methods of *in situ* conservation of plant genetic resources, creating agroecosystems to produce sustained yields based on the adaptation of crops to local ecological conditions, and regional needs (Alcorn, 1997).

Alcorn (1997), in her paper “The scope and objectives of Ethnobotany in a developing world,” explains in detail how to conduct research based on an ethnobotanical perspective. This section briefly presents his viewpoint, which is key to the current research. Regarding the type of information to analyze, a text of ethnobotanical research should cover all the aspects relevant to the ecological characteristics of the study zone, use and management of vegetation, native people’s holistic worldview regarding plants, nature, and life.

To be specific, the ecological, economic, and socio-cultural roles or functions of both humans and plants in the study area should be described in the ethnobotanical text. Moreover, the functions refer to both the characterization as well as the performance itself. Both humans and plants play diverse parts that vary according to the context. For instance, humans play roles such as farmers or consumers who domesticated plants, buyers or agents who sell the product, etc. Likewise, plants fulfill roles of crop, domesticated plant, food, medicine, sales product, etcetera.

Ethnobotanists should consider employing methods from other disciplines such as anthropology, botany, geography, chemistry, pharmacology, and edaphology to collect data regarding different aspects mentioned above. Although various approaches are used, the dialectical process is fundamental in ethnobotanical research.

Agreeing with Hernández (1970), the author suggests asking a series of specific questions pertinent to the use, management, and conservation of plants. For instance, questions such as: what plants are useful? Why are those plants useful? Which plants are considered as resources? Serve to analyze human activities and their organizations and plant functions. Researchers in this field should observe from the botanist point of view and apply cultural and scientific perspectives.

As interpreting and integrating the human and plant correlation is difficult for people who neither belong to native culture nor a biologist, and to overcome biases in the ethnobotanical investigation, it is crucial to understand the expressed mute language of native people. In other words, as the attitude of the local people reflects their holistic worldview and perception of the environment, it is essential to make careful observations on their philosophy, which is most of the time unexpressed by words.

Regarding the role of ethnobotanical knowledge in development plans, as plants provide raw materials that are linked to cultural expressions and the domestic economy, ethnobotanical knowledge is frequently retained and transmitted by the community members for the survival of the next generations. Thus, undoubtedly, ethnobotanical knowledge (representing the ecological, economic, and socio-cultural aspects) contributes to rural development.

Moreover, ethnobotanical research text provides valid information regarding the use, management, and conservation of local resources and the effects of human activities, and the resilience of local people in the face of diverse challenges. Hence, as local problems should be addressed based on specific local solutions, development programs should emphasize an ethnobotanical approach to design and implement policies to contribute to sustainable rural development. Also, collecting systematic information based on the Ethnobotanical research approach suggested by Alcorn (1997) is very important in the current study zone where native people's perception is difficult to observe and interpret.

2.7 Resilience concept and sustainable development

2.7.1 Resilience theory

The concept of resilience has a long and multi-disciplinary (economics, engineering, infrastructure, behavioral, social science) history. There are different opinions regarding the origin of the concept, but it can be traced in physics, mathematics (Bodin and Wiman, 2004), and psychology (Waller, 2001; Manyena, 2006). However, the descriptive term of resilience was initially proposed in ecological literature by Holling (1973) in his seminal paper and defined as a "measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables".

Meanwhile, the concept was widely adopted as an approach to analyzing different complex dynamic systems such as the ecological, social-ecological, and socio-economic (Levin *et al*., 1998; Folke, 2006; Anderies, Ryan, and Walker, 2006); hence the concept of resilience has been frequently redefined and extended to other dimensions. In other words, it played different roles. The term was used as a goal (to achieve an outcome), analytical tool (to understand the problem and find solutions), a metaphor (to break disciplinary or sectoral silos), indicator (as part of development objectives or sustainability), heuristic (as a model to describe the system) and buzzword to refer to strategy (Béné *et al*., 2017; Tanner, Bahadur, and Moench, 2017).

As there is no universal or standard definition and the existing definitions vary according to the context, it is essential to distinguish engineering and ecosystem resilience concepts. It is mainly because, in recent years, numerous explanations have increased from the above two notions. According to Holling (1996), engineering resilience refers to changing aspects or dynamics close to equilibrium and is defined as “the ability of a system to return to equilibrium or a steady-state.” It has long been used to describe the stability or elasticity property (i.e., the speed of return to a stable state) of materials mentioned by Grimm and Wissel (1997).

Simultaneously, the concept of ecosystem resilience has evolved initially from the above-mentioned ecological description of the term (Holling, 1973). It refers to changing aspects far from any equilibrium (i.e., flexibility and instability with a tendency to change into new states), being as “the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior” (Gunderson and Holling, 2002).

In short, a resilient system in engineering resilience bounces back towards equilibrium, and in ecological resilience bounces forth far from equilibrium, i.e., step forward. Later the definition of ecosystem resilience with interchangeable words was used to refer to ecological resilience. A wide range of other definitions has also emerged in different works from the late 1980s. For example, Brand and Jax (2007) present ten extended definitions from an ecological perspective. The authors classify them into different categories (descriptive, hybrid, and normative concepts) and classes (environmental, social, and sustainability science).

Other sectors used different terminologies (such as security or risk resilience, climate resilience, disaster resilience, infrastructure resilience, etc.) and appropriated the concept according to the context. For instance, the studies of interactions between humans and their environments, i.e., social-ecological systems (SES), apply the concept of resilience by incorporating the ideas of adaptation, self-organization, and learning in addition to the general ability to resist disturbances (Cutter *et al*., 2008; Folke, 2006; Folke *et al*., 2010). This idea of SES resilience differs from the initial idea of returning to a state of normality without changing (i.e., the capacity of an agroecosystem to return to its original state after disturbances). This is mainly due to the understanding of multiple equilibrium states and accepting that change is inevitable.

Table 2. Definitions of the concept "Resilience."

Organizations	Definitions	Sources
United Nations Development Programme (UNDP)	Resilience is "an inherent as well as acquired condition achieved by managing risks over time at the individual, household, community, and societal levels in ways that minimize costs, build capacity to manage and sustain development momentum and maximize transformative potential."	UNDP, 2013.
The United Kingdom Department for International Development's (DFID)	Disaster resilience is "the ability of countries, communities, and households to manage change, by maintaining or transforming living standards in the face of shocks or stresses - such as earthquakes, drought or violent conflict – without compromising their long-term prospects".	DFID, 2011
Sustainable Development Goals (SDG)	The capability of individuals, communities, and systems to deal with potential vulnerabilities, shocks, and disturbances by developing absorptive (withstanding shocks and stresses), anticipatory (foreseeing shocks and stresses), and adaptive capacities (changing), usually referred to as the "3As."	Bahadur *et al.*, 2015; Holling, 1973
Resilience Measurement Technical Working Group (RM TWG)	"The capacity that ensures stressors and shocks do not have long-lasting adverse development consequences."	Food Security Information Network [FSIN], 2014;
United States Agency for International Development (USAID)	"The ability to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth."	Frankenberger, Mueller, Spangler, and Alexander, 2013
Food and Agricultural Organization-Resilience Index Measurement Analysis (RIMA-II)	"The capacity of a household to bounce back to a previous level of well-being (for instance, food security) after a shock."	FAO, 2016b

In other words, the resilience of SES allows them to return to the steady-state and adapt (capacity to adjust) or transform (ability to cross thresholds) into new conditions to reach new states. Therefore, SES considers the adaptability and transformability aspects of resilience (Walker, Holling, Carpenter, and Kinzig, 2003). Notwithstanding their differences and similarities, all these definitions and interpretations emphasize the main idea that resilience is the ability of the system to retain structure and function after disturbances and adapt to change. As there are many adopted definitions in different fields, Table 2 presents some basic context-based definitions which are not mentioned above but used in other frameworks or approaches to evaluate resilience.

2.7.2 The relevance of resilience to sustainable development

Resilience is a fundamental property of the system and means limiting vulnerability and promoting sustainability (Resilience Alliance, 2010; Serfilippi and Ramnath, 2018). Resilience framework is a multi-level factor and is applied at three levels: individual (micro-level), community (Meso level), and system or society (macro-level). An individual or a system becomes vulnerable when it loses its resilience (i.e., the ability to absorb changes). Even small shocks could be devastating to vulnerable systems (Kasperson and Kasperson, 2005).

In other words, as resilience declines, slowly but surely, even more, minor disturbances could push the system into a different regime, or "basin of attraction," with substantial differences in its structure and function and thereby affect its sustainability. Often these kinds of transitions between states or regimes are slow and gradual. Still, at other times it can be abrupt or even unnoticed until it is too late, e.g., the desertification of the Aral Sea and the collapse of the cod fishery off the coast of Newfoundland, Canada (Resilience Alliance, 2010).

Agencies or actors who are interested in building resilience should not overlook the probability that, in some cases returning to the original state or regime is not always a suitable or feasible option. In other words, resilience is not always positive. For example, systems trapped in a cycle of poverty or ecological degradations could resist transforming towards favorable conditions (Cabell and Oelofse, 2012).

And in other cases, it is impossible or difficult to reverse the effects of the shift between alternate states, i.e., from the new to the old regime, for instance, modifications such as melting Earth's glacier and sea ice, transitions from coral reefs to algae-covered rocks, from grasslands to shrub-dominated landscapes, from clear to cloudy water in freshwater lakes. Moreover, changes in sea level, fish production, grazing potential, and tourism or recreation opportunities are associated with each of these shifts (Resilience Alliance, 2010).

And shifting to a new regime or returning to the equilibrium state is desirable or not, depending on the outcomes or trajectories of the structure and function of the system (Scheffer and Carpenter 2003; Walker, Abel, Anderies, and Ryan, 2009). Therefore, building resilience capacities (absorptive, anticipatory, and adaptive) are essential both in addressing system-level issues of policy coordination, cooperation, and integration, as well as at the individual and community levels in empowering citizen mobilization and empowerment to facilitate a positive change at different levels (WHO, 2017).

The resilience profile has increased in the above context, particularly from the adopted resolution of Transforming our world: the 2030 agenda for sustainable development by the United Nations General Assembly on 25 September 2015. And it highlights that resilience is a central mechanism or fundamental element to build sustainable societies, which is key to progress towards sustainable development. In addition, some of the United Nations Sustainable Development Goals (SDGs) suggest (Table 3) finding a solution to build resilience at various (mainly at system) levels by addressing the vulnerability of the planet (UN, 2015; Lovell, Bahadur, Tanner, and Morsi, 2015).

Table 3. Reference to the term “Resilience” in SDGs.

SDGs	Goals	Targets
SDG 1	End poverty in all its forms everywhere.	1.5. By 2030, build the **resilience** of the poor and those in vulnerable situations and reduce their exposure and vulnerability to extreme climate-related events and other economic, social, and environmental disasters.
SDG 2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.	2.4: By 2030, ensure sustainable food production systems and implement **resilient** agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters, and that progressively improve land and soil quality
SDG 9	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation related to industry and innovation and calls for building **resilient** infrastructures.	9.1: Develop quality, reliable, sustainable, and **resilient** infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, focusing on affordable and equitable access for all. 9.a: Facilitate sustainable and **resilient** infrastructure development in developing countries through enhanced financial, technological, and technical support to African countries, least developed countries, landlocked developing countries, and small island developing States.
SDG 11	Make cities and human settlements inclusive, safe, **resilient,** and sustainable.	11.b: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, **resilience** to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels. 11.c: Support least developed countries, including financial and technical assistance, in building sustainable and **resilient** buildings utilizing local materials.
SDG 13	Take urgent action to combat climate change and its impacts.	13.1: Strengthen **resilience** and adaptive capacity to climate-related hazards and natural disasters in all countries.
SDG 14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.	14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their **resilience,** and take action for their restoration to achieve healthy and productive oceans.

(Source: UN, 2015).

Furthermore, the United Nations Development Program (UNDP) also addressed the need to build resilience to face the risks caused by the environmental and socio-economic crises during the 2017 Istanbul Development Dialogues (UNDP, 2017). These organizations pursue resilience mainly to reduce the likelihood and the impact of extreme adverse events and help people recover from the effects. Also, they consider that applying resilience thinking in different fields could provide a means of analyzing, measuring, and implementing the sustainability of SES (Levin *et al.*, 1998).

Besides, resilience helps to focus on the short-term response of the systems to shocks and stresses more constructively and creatively instead of long-term equilibrium or stability, which sometimes erodes resilience and facilitates the breakdown of the system. Moreover, changes in a resilient system provide more opportunities for development, novelty, innovation (FAO, 2018), and sustainability of Earth systems.

2.8 Diverse approaches to assess resilience

2.8.1 Resilience measurement in different fields

Most recently, the application of resilience theory extends beyond ecology to health, food security, development, etc. However, even if this increasing acknowledgment influenced scholars to develop an array of approaches, standard and consistent metrics or mechanisms are lacking or underdeveloped (Quinlan, Berbés-Blázquez, Haider, and Peterson, 2015; Klein, Nicholls, and Thomalla, 2003; Manyena, 2006; Martin-Breen and Anderies, 2011). This is mainly due to measuring the abstract and multi-dimensional, and complex nature of resilience theory (Carpenter, Walker, Anderies, and Abel, 2001; Cumming *et al.*, 2005).

Numerous frameworks, approaches, tools, and methods were found in the literature to quantify resilience based on access to food, activities, subjective perceptions, costs of resilience, functionality, indicators, and characteristics. International development organizations have developed several conceptual and analytical models, multiple sets of qualitative and quantitative indicators, participatory assessments, statistical analyses, and metrics to measure or assess resilience. Many resilience frameworks focused on ecological or social-ecological systems, sustainable livelihoods, and disaster risk reduction.

Others focused on climate change, development, and community resilience (Winderl, 2014; Nguyen and James, 2013; Frankenberger, Constas, Nelson, and Starr, 2014; Lisa, Schipper, and Langston, 2015; Bahadur *et al.*, 2015; Serfilippi and Ramnanth, 2018). According to Quinlan *et al. (*2015), assessment approaches aim to understand the system dynamics of resilience, whereas measurement approaches aim to capture and quantify resilience in a rigorous and repeatable way. Given the constraint that stability and vulnerability were not easily measured or observed, most of the approaches employed either direct (descriptive) or indirect (inferential) proxy measure according to the context to assess resilience (Luers, Lobell, Sklar, Addams, and Matson, 2003; Bennett, Cumming, and Peterson, 2005; Carpenter, Bennett, and Peterson, 2006; FAO, 2016b; Patt, Schröter, Vega-Leinert, and Klein, 2008; Hinkel, 2011).

In other words, these approaches identify key attributes or components or capacities of the resilient system as measurable indicators using the inductive method. Then, the assigned objective indicators for each feature of the system were obtained and aggregated to construct a resilience index to understand factors that characterize the system's resilience (FSIN, 2014; Jones and Tanner, 2017; Clare, Conway, Graber, and Jones, 2017). For example, in the context of food security, household and community characteristics (such as income, assets, education, gender, skills, economic status, infrastructure, etc.) are used as proxies to measure the level of resilience. As these context-based proxies are assumed to be representative, therefore, the rigor and replicability of this approach remain debatable (Frankenberger, Constas, Nelson, and Starr, 2014; Ansah, Gardebroek, and Ihle, 2019).

To avoid the limitation mentioned above of the use of indicators, some authors suggested alternative approaches. For instance, Béné (2013) suggested using transactional cost as an essential independent metric to assess resilience across scales and dimensions. According to the author, this cost should include ex-ante and ex-post investments, losses, sacrifices, and individual or collective level of costs to ‘go through a shock or an adverse event.

Other resilience measurements used subjective methods as an alternative approach to measuring resilience. For instance, the BRACED (Building Resilience and Adaptation to Climate Extremes and Disaster) program of Rapid Response Research (RRR) in Myanmar used subjective tools (based on respondents' perception and knowledge regarding their capacities to deal with risk) to measure resilience instead of objective approaches, i.e., expert judgment and external verification to decide people's capacity to deal with the threat (Jones and Tanner, 2017; Jones, 2018).

Contrary to context-dependent indicators, unique approaches apply mathematical models to quantify resilience (e.g., Fletcher, Miller, and Hilbert, 2006; Sanders, Sungwoo, and WooSung, 2008). Some models, such as the technical assistance to non-governmental organizations (Frankenberger, Spangler and Langworth, 2012) and the Department for International Development (DFID, 2011), apply the system-wide approach to describe and assess resilience.

Other models such as FAO's RIMA I & II (Frankenberger *et al*., 2013; USAID, 2013), Oxfam (2013, 2015), and the Africa climate change resilience alliance (ACCRA) (Tyler *et al.*, 2014), intend to define and measure multi-dimensional aspects of resilience at community levels by considering change over time, during or after a shock, or between target and control populations. Also, some of these models employed various tools such as multivariate techniques like factor analysis, principal component analysis, structural equations modeling and multiple indicators multiple cause models, regression analysis to quantify resilience capacities.

Other tools, such as the Resilience Assessment Workbook developed by Resilience Alliance (2010), offered guidelines to assess the resilience of the dynamic change involved in the complex Socio-ecological systems (SES) by answering the question “the resilience of what, to what,” which was initially proposed by Carpenter *et al.* (2001). This assessment framework encompasses five main stages: 1) Describing the system; 2) Understanding system dynamics; 3) Probing system interactions; 4) Evaluating governance; 5) Acting on the assessment.

Methods such as modeling timelines, scale analysis, scenarios, network analysis, and participatory discussion are used to identify and assess the system's key attributes. As this process is iterative and reflexive at each stage, the constant revision of earlier steps is inevitable. Therefore, it helps to monitor potential system thresholds continuously to update knowledge. Resilience system analysis is another tool and has been designed to facilitate a multi-stakeholder resilience analysis workshop that provides a roadmap to boost the resilience of communities and societies and integrate the results of the analysis into their development and humanitarian programming. It is a flexible approach and different from risk management analysis. It uses a systems approach (OECD, 2014).

There are different quantitative and qualitative methods to determine resilience, and this section just covered some of them. Still, many resilience measurement approaches are emerging in a wide range of disciplines. This is mainly due to the lack of consensus about a standard framework. The major limitation is that it will be difficult to understand the operationalization (or explanation and interpretation) of several resilience measurement frameworks without a good literature review.

2.8.2 Resilience measurement in agricultural systems

The advantages of using indicators in the resilience approach for complex dynamic systems such as SES, including agroecosystems, were recognized considerably by many authors. For instance, Darnhofer, Bellon, Dedieu, and Milestad (2010) coincide with the works of Bennett *et al.* (2005) and Carpenter *et al.* (2006) and agree that developing ‘general rules of thumb’ using a set of indicators or surrogates is a more practical approach to assess resilience in farming or other industrial systems to facilitate resilient orientation to farmers or mediators.

Concurring with Darnhofer *et al*. (2010), Cabell and Oelofse (2012) developed a set of indicators (called behavior-based indicators) to assess the resilience of agroecosystems and followed the same technique applied to the use of biotic indicators to monitor ecosystems (Buechs, 2003). They concluded that the presence of these behavior-based indicators in an agroecosystem indicates that the system is resilient—the absence of the signals' vulnerability that requires intervention.

Other studies about agricultural systems resilience towards salinity intrusion in the coastal areas of Vietnam (Nguyen, Renaud, Sebesvari, and Nguyen, 2019) implement a subjective resilience assessment based on farmers' perception of three resilience components: 1) sensitivity; 2) capacity to recover; 3) capacity to change or transform to a new state. Córdoba, Triviño, and Calderón (2020) compared two agricultural communities in Brazil and Colombia based on agrarian structures and capacity of peasant agency as critical social factors limiting agroecosystems' resilience and developed 17 weighted variables to quantify it. Other methodologies employed ecological and productive indicators such as vegetation diversity, landscape complexity, subsistence, technology, and input dependence (Adger, 2000; Milestad and Darnhofer, 2003; Speranza, 2010; Jacobi *et al.*, 2013).

2.9 Review of other methods considered in this study

2.9.1 Review of considered qualitative methods

According to Levins (2015), the qualitative mathematic approaches could help understand the complex agroecosystems where the mathematical equation is unknown to analyze some variables. Thus, this study considered several qualitative methods mentioned in Table 4 to collect data from the field.

Table 4. Review of qualitative methods.

Method	Description	Source
Semi-structured interview	A semi-structured interview is a qualitative method of research used widely in social sciences. Unlike a structured interview (that has a rigorous set of questions), it is open. It also easily allows having a conversation with participants using guidelines based on the objective of the study.	Martin, 2004; Bernard, 2000 & 2006.
Participatory and direct observation	This method reduces the subjectivity of the researcher and helps establish a relationship between participant and researcher.	Albuquerque, Cruz Da Cunha, Lucena, and Alves, 2014a; Albuquerque, Lucena, and Neto, 2014b;
Questionnaires	This technique is applied when time in the field is limited. And it allows obtaining limited answers about management, use, and conservation of resources in homegarden.	Bernard, 2011.
Free listing	It is a method that documents the use of the plants that a participating researcher can quote at a specific time.	Geilfus, 2002;
Ethnobotanical exploration	Ethnobotanical exploration should consider the following six experiences: 1) background information of the study problem; 2) ecological, environmental characteristics of the study area; 3) man's influence in management, use, and conservation of plants; 4) morphological and ecological characteristics of each species; 5) The knowledge accumulated in millennia, takes time to collect; and 6) exploration must be a dialectical process.	Hernández, 1970; Alexiades, 1996.
Surveys	It is the technique of gathering data by asking the participants questions using a formal list of questionnaires.	Geilfus, 2002.

2.9.2 Review of considered quantitative methods

Diversity index analysis

Diversity indices mainly measure the species richness, abundance in a place through an inventory of species. To estimate these indices, there are several proposals, among the most important are: Margalef diversity index, Shannon index, and Simpson index.

Multi-criteria decision analysis of FlowSort

Multi-criteria decision analysis (MCDA) methods support the decision-maker in their unique and personal decision process. As most human problems have a multicriteria nature, these methods incorporate subjective or preference information provided by the decision-maker, thereby finding a compromise solution to a multi-criteria problem (Roy, 1981; Zopounidis and Doumpos, 2002; Ishizaka and Nemery, 2013).

One of the MCDA methods utilized in this study was the Flowsort analysis. It is an outranking sorting method proposed by Nemery and Lamboray (2008) based on the ranking methodology of PROMETHEE. FlowSort assignment rules are based on the relative position of an alternative concerning the reference profiles in terms of unicriterion positive (leaving), negative (entering or incoming), and net flows (Brans and Vincke 1985; Zopounidis and Doumpos, 2002; Ishizaka and Nemery, 2013; Brans and. De Smet, 2016).

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3. HOMEGARDENS: STATE OF THE ART

THE SCOPE AND CONSTRAINTS OF HOMEGARDENS FOR SUSTAINABLE DEVELOPMENT: A REVIEW*

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Review [Revisión]

THE SCOPE AND CONSTRAINTS OF HOMEGARDENS FOR SUSTAINABLE DEVELOPMENT: A REVIEW †

[ALCANCES Y LIMITACIONES DE LOS HUERTOS FAMILIARES PARA EL DESARROLLO SOSTENIBLE: UNA REVISIÓN]

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SUMMARY

Background. Considering the current importance of recognizing the potential of traditional agroecosystems, including homegardens in the sustainable development of many rural and urban communities, strategists and scientists around the world are showing increasing interest in their study. **Objective.** Analyze the scientific literature relevant to the scope and constraints of homegardens (HGs), and to identify gaps and research perspectives, especially for indigenous communities in Mexico. **Methodology.** A total of 335 studies published in the last decades (1986-2020) were collected from different databases using predefined keywords. All publications were organized and stored in the Zotero (2018) program. The trends of all the publications were analyzed using NVivo 12 Plus software. **Results.** The number of publications increased from the year 2000. About 70% of the publications analyzed were research articles in english. Of the total studies examined 239 (71.35%) were conducted in different parts of the world, of which 30% from Asia and the remaining 96 (28.65%) from Mexico, primarily in tropics. Most of these studies focused on ecological (62.98%), economic (20.29%), cultural (13.43%), social (7.46%) and multifunctional features (12.23%) of HGs. The same pattern was identified in the case of Mexico, with studies of 10.74%, 5.07%, 5.67%, 0.597%, and 3.58% focused on ecological, economic, cultural, social and the multifunctionality features of HGs respectively. **Implications.** The analysis of the scope and limitations of HGs contributes to identifying the need to carry out transdisciplinary research that reflects their whole dynamics as agroecosystems, in which, in addition to the ecological environment, there are various cultural aspects considered important in the indigenous communities of Mexico. **Conclusions.** The publications emphasized the importance of homegardens to provide multiple ecosystem functions and services to enhance human well-being. However, future research should reevaluate HGs based on a holistic multi-functional agriculture approach to promote them as one of the strategies conducive to improve family well-being. Also, it is suggested to evaluate the degree of sustainability of HGs based on its resilience and adaptation capacity to confront current challenges.
Keywords: agroforestry systems; biocultural heritage; livelihood strategy; multifunctional agriculture; traditional agroecosystems.

RESUMEN

Antecedentes. Considerando la importancia actual de reconocer el potencial de los agroecosistemas tradicionales incluidos los huertos familiares en el desarrollo sostenible de muchas comunidades rurales y urbanas, los estrategas y científicos del todo el mundo están mostrando un interés creciente en su estudio. **Objetivo.** Analizar la literatura científica relevante al alcance y las limitaciones de los huertos familiares (HF), e identificar las brechas y las perspectivas de investigación, especialmente para las comunidades indígenas en México. **Metodología.** Se recopilaron 335 publicaciones de las últimas décadas (1986-2020), de diferentes bases de datos utilizando palabras clave predefinidas. Todas las publicaciones se organizaron y almacenaron en el programa Zotero (2018). Las tendencias de todas las publicaciones se analizaron utilizando el software NVivo 12 Plus. **Resultados.** El número de publicaciones

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aumentó a partir del año 2000. Alrededor del 70% de las publicaciones analizadas fueron artículos de investigación en inglés. Del total de estudios examinados, 239 (71.35%) se realizaron en diferentes partes del mundo, de los cuales el 30% de Asia y los 96 restantes (28.65%) de México, principalmente en los trópicos. La mayoría de estas publicaciones se centraron en las características ecológicas (62.98%), económicas (20.29%), culturales (13.43%), sociales (7.46%) y multifuncionales (12.23%) de los HF. Se identificó el mismo patrón en el caso de México, con estudios de 10.74%, 5.07%, 5.67%, 0.597% y 3.58% enfocados en las características ecológicas, económicas, culturales, sociales y multifuncionales de HF respectivamente. **Implicaciones**. El análisis de los alcances y las limitaciones de los HF contribuye a identificar la necesidad de realizar investigaciones transdiciplinarias que refleje su dinámica total como agroecosistemas en los que, además del medio ecológico, existen diversos aspectos culturales considerados importantes en las comunidades indígenas de México. **Conclusiones.** Las publicaciones enfatizaron la importancia de los HF para brindar múltiples funciones y servicios ecosistémicos con el fin de mejorar el bienestar humano. Sin embargo, las investigaciones futuras deben reevaluar los HF basados en un enfoque holístico de la agricultura multifuncional con el fin de promover estrategias conducentes al mejoramiento del bienestar familiar. Además, se sugiere evaluar el grado de sostenibilidad de los HF en función de su capacidad de resiliencia y adaptación para enfrentar los desafíos actuales.
Palabras clave: sistemas agroforestales; patrimonio biocultural; estrategia de medios de vida; agricultura multifuncional; agroecosistemas tradicionales
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INTRODUCTION

Homegarden (HG) has been identified as the oldest and complex land-use or agroforestry system that has evolved through generations in different parts of the globe, especially in the tropics. It is considered as one of the major forms of sustainable agricultural or food production activity commonly practiced by diverse cultural and ethnic groups of people all over the world primarily for subsistence (Torquebiau, 1992; Kumar and Nair, 2006; Krishnamurthy and Krishnamurthy, 2016; Vibhuti et al., 2018).

In Mexico, HGs play a vital role in the lifestyle of the indigenous population of more than 68 ethnic groups (INALI, 2008), distributed throughout the country. Also, it is considered as a sub-system of the traditional agroecosystems that predominate in the rural landscape of the nation as well as it is recognized as an integral part of the family agriculture system that provides food and other basic requirements to many native people in Mexico (Caballero et al., 2010; Mariaca, 2012; Ordoñez Diaz et al., 2018a; Castañeda- Guerrero et al., 2020).

In the last few decades, especially, from the 80's, there are several studies all around the globe that highlight the potential of HGs to contribute to sustainable development. This is mainly due to their ability to manage, use as well as conserve natural resources efficiently compared to commercial agricultural practices and at the same time provide multiple fundamental ecological functions (such as nutrient cycling, photosynthetic route enhancement, resistant to plant diseases) and services (such as food, recreation, habitat) which are primordial for inclusive rural development (Monroy and García, 2013; García-Flores et al., 2016a; Krishnamurthy et al., 2017; Muhammad et al., 2017).

Although the importance of HGs recognized worldwide, on one hand, still these systems have not been given priority in the national or international development agenda as an inclusive development strategy and on the other hand, the management, conservation, and appreciation of agrodiversity associated with these traditional systems in future remains uncertain due to the changing demands and expectations of the growing population regarding food or wealth.

To be specific, currently, traditional practices including HGs are vulnerable and confront series of environmental, economic, and socio-cultural crises such as climate change, loss of biodiversity, the irrational extension of the agricultural frontier, cultural erosion, migration, rapid urbanization, etc. Consequently, endangering the livelihood as well as the sustainability of the local people who depend on them, especially, as recognized in the rural parts of Mexico (Cano-Ramírez et al., 2012; Mohri et al., 2013, Cano Contreras, 2015; González, 2018; Ordoñez Diaz et al., 2018a). Moreover, the accumulated biocultural knowledge transmitted from generation to generation could vanish by disrupting the way of life involved in this kind of traditional practices (Toledo and Barrera-Bassols, 2008; Boege, 2008; Lope-Alzina, 2012; Ordoñez Díaz et al., 2018b).

Under these conditions, it is essential to review the current status, importance and persistence of the HGs towards the above-mentioned challenges. In this context, this study aims to gather, systematize, and analyze a wide set of scientific literature relevant to the scope and limitations of homegardens in the sustainable development of peasant families involved in their management as well as to identify existing gaps and study perspectives in this field of research, especially in Mexico.

In summary, the intention of this review is first, to document the current state of homegarden knowledge, and second, to provide compiled information as a basic reference to perform an updated review in the future. For this purpose, an extensive literature review relevant to the present study carried out using Meta-analysis method. Based on the outcome of our analysis, we ultimately discuss, why multifunctional homegardens despite its potential are vulnerable and how to enhance these systems to protect and promote as an alternative strategy for livelihood in the sustainable developmental policy programs.

MATERIALS AND METHODS

A search of publications related to homegardens at a global level was carried out. First, an extensive and systematic literature review was developed on the subject of interest using free or public search engine databases such as ScienceDirect, Google Scholar, Academia, ResearchGate, Scientific Electronic Library Online (SciELO), FreeFullPDF, and CONRICyT (initials in spanish stands for, Consorcio Nacional de Recursos de Información Científica y Tecnológica). The above-mentioned search engines allowed to have access to scientific articles relevant to the theme in different journals such as Agrosystems, Economic Botany, Elsevier, Ethnobotany, Nature, Terra, Tropical and Subtropical Agroecosystems, and the Mexican Science and Technology magazines of CONACYT (initials in spanish stands for, Consejo Nacional de Ciencia y Tecnología).

Second, different combinations of a predefined list of eleven key phrases both in Spanish and English were used: 1) Homegardens + Ecological importance, 2) Homegardens + Economical importance, 3) Homegardens + Sociocultural importance, 4) Homegardens + Multifunctional agriculture, 5) Homegardens + Sustainability, 6) Homegardens + Climate change, 7) Homegardens + Resilience, 8) Homegardens + Agroforestry, 9) Homegardens + Agroecosystems, 10) Homegardens + Mexico, 11) Homegardens + opportunities and limitations.

Third, the search was delimited from January 1986 to January 2020, considering only the published articles in indexed journals. Due to the lack of peer review process, the current study did not consider the valuable information found in “grey literature” (e.g., technical reports, conference abstracts, graduate and undergraduate theses). Fourth, all the publications found in the search were organized in a database according to the title, author, type and year of publication.

Fifth, they were stored in the reference management program called Zotero (2018), in the alphabetical order according to the American Psychological Association (APA 7th edition) standard. Sixth, all the references stored in the Zotero were converted in the RIS (Research Information Systems) format to store as a compiled file in the computer. Seventh, the compiled file was exported to the software program of qualitative research, NVivo 12 plus (QSR International, 1999), where a frequency analysis of words with a minimum of six characters was carried out. This number of characters was selected, since the keywords related to the topics of the publications contain at least six or more characters, for example, Mexico, homegarden.

The word frequency analysis allowed identifying the most representative keywords in all documents, which were detected in the word cloud (Figure 18) according to their dominance of font size, in the first five levels. These keywords allowed selecting the publications that contained three or more keywords in the abstract. Finally, the selected publications were classified based on parameters called nodes or themes. These codifications allowed to evaluate each publication based on its research topic. Also, these results facilitated the focus of the discussions to analyze the publications of homegardens at a global scale including Mexico, and perhaps the most important, they will contribute to strengthening research on home gardens in Mexico as pillars of agricultural sustainability, both ecologically and culturally.

RESULTS AND DISCUSSION

Across the globe, including Mexico, HGs have been studied extensively for different reasons. By analyzing the documented literature by a wide range of disciplines with a distinct research focus in a specific location, this review presents the following synthesis to update knowledge in the homegarden research topic.

Research publications in the homegarden field

The results of this database indicate that more than 70% of the research papers considered in this review were written in English and the rest in Spanish, as well as the type of publications analyzed, were mostly research (267 papers, i.e., 79.7%) and review (35 papers, i.e., 10.44%) articles. The rest of the documents belong either to book or book chapters. Regarding the place of research, more than 239 (71.35%) studies were carried out in different parts of the world, primarily in tropical regions. And the remaining 96 (28.65%) studies were carried out in different states of Mexico. Regarding the number of publications, overall, research studies in this topic is increasing in the last few decades, especially from the 1980s. The summary of all these results is shown below (Figure 17).

Word frequency analysis

The word frequency analysis was conducted based on the criteria of the minimum six characters of words as well as the 500 most frequent words from a total of 335 publications. The results obtained were filtered by deleting the irrelevant or derived or general words such as abstract, according, amount, examine, hypothesis, maximum, etc. The same procedure was applied for the 250, 100 and 50 most frequent words. This procedure facilitated to distinguish between the most and the least frequent words, which in turn simplified to select and compare the most representative keywords relevant to the topic.

Based on the results generated in the different levels of frequency analysis, a total of 22 most frequent keywords with maximum 16 characters were selected that represent 8.8% of the total words: species, homegardens, agroforestry, management, traditional, social, economic, conservation, biodiversity, development, cultural, ecological, knowledge, composition, structure, Mexico, ecosystem, nutrition, livelihood, agrobiodiversity, sustainability, biocultural. Also, a total of five less frequent keywords with maximum 15 characters that represent 2% of the total words: resilience, adaptability, agrodiversity, vulnerability, multifunctional, multipurpose.

The most and least frequent keywords could be differentiated based on the dominance of each word's font size in the following image (Figure 18). Some less frequent words such as resilience, agrodiversity not even shown in the image due to its low rate or rank of frequency. The selected keywords allowed to generate 10 principal themes or nodes (Table 5, Figure 19), which in turn facilitated to codify and then categorize or classify all publications into certain nodes based on their research focus. Many studies belong to more than one category.

The results of the categorized publications on homegarden research around globe indicate that: i) more than 62.98% of the papers were focused on the potential to provide diverse ecosystem services by safeguarding species, structural and functional diversity. Out of which, plant or species diversity issues from ethnobotanical perspective were the most prevalent studies; ii) about 20.29% of the research analyze the role to provide income or savings that helps to meet economic needs of the family through the sale or use of garden products throughout the year; iii) around 13.43% of the studies emphasize the potential to protect cultural diversity by promoting associated traditional ecological knowledge of the native people; iv) even though HGs scope to provide social benefits is higher, the results identified, only 7.46% of the papers encompass the social aspects; v) only, 12.23% of investigations highlight the multifunctionality feature using the holistic approach of sustainable development, i.e., environmental, economic, and socio-cultural functions; and vi) there are very few studies relevant to the assessment of the sustainability of HGs based on its resilience and adaptation capacity which is shown in the graph (Figure. 19).

According to the results obtained in case of Mexico indicate that although majority of studies identified explore the ecological (10.74%), economic (5.07), and cultural (5.67%) aspects of homegardens, there are very few studies (0.597%) given priority to the social relevance (Table 5). Besides, very lower percentage of HG studies considered (3.58%) analyze the multifunctionality character and its contribution to sustainable development. Overall, the classification of the publications based on nodes facilitated to select and compare research focus and findings in the HG field throughout the globe. Also, it allowed us to identify the current status in this field of research, which in turn facilitated to identify gaps and perspectives, especially in Mexico.

Homegarden: A traditional agricultural practice

Several research studies have been carried out in different parts of the world through which different aspects of HGs have been addressed until now, however, most of them remained descriptive. A clarification regarding the origin, definition and general characteristics of this traditional production system is essential to update reader's comprehension relevant to its historical context and biophysical aspects. In this context, as one of the results, the current literature review presents a summary of the overall description of this ancestral land-use practice in the following sections: 1) the concept of HG, 2) historic development of HG, 3) distribution of HG, 4) characteristics of HG, 5) types of HG, and 6) management of HG.

The concept of HG

There is a lack of universal term and definition to refer to homegarden (also spelt as a home garden). Numerous studies have been designated HGs using different terms that vary according to the culture, ethnic, language, and dialect of the distinct groups of people living in different geographical locations. For example, there are terms such as mixed-garden horticulture (Terra, 1954), dooryard gardens (Wilhelm, 1975), house garden (Stoler, 1978), home-garden (Wiersum, 1982), kitchen garden (Brierley, 1985),

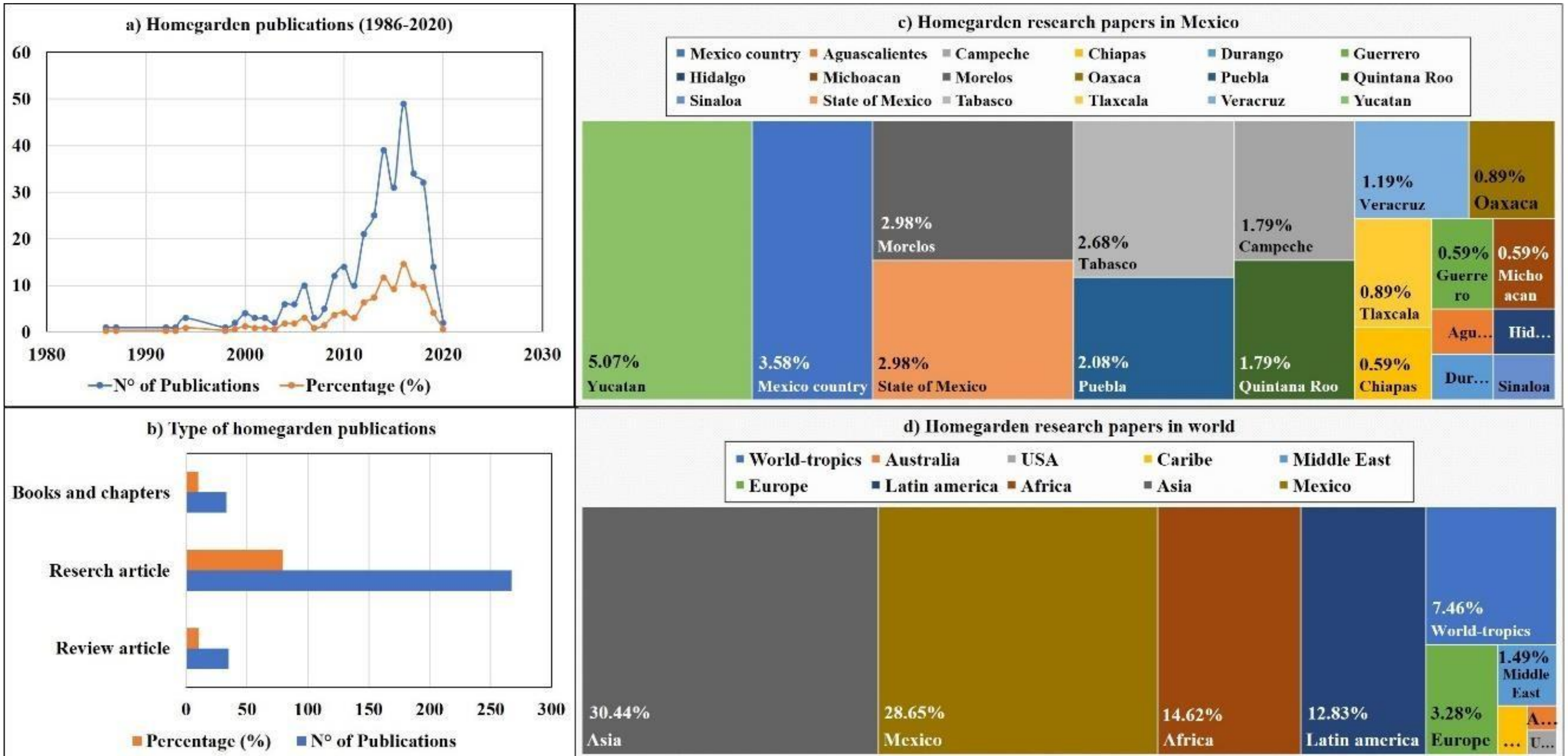

Figure 17. The categorized homegarden publications in the current study were represented in graphs that indicate: a) publications trend from 1986-2020; b) the type of documents considered; c) percentage of studies analyzed in different regions of Mexico and d) percentage of studies reviewed from different parts of globe.

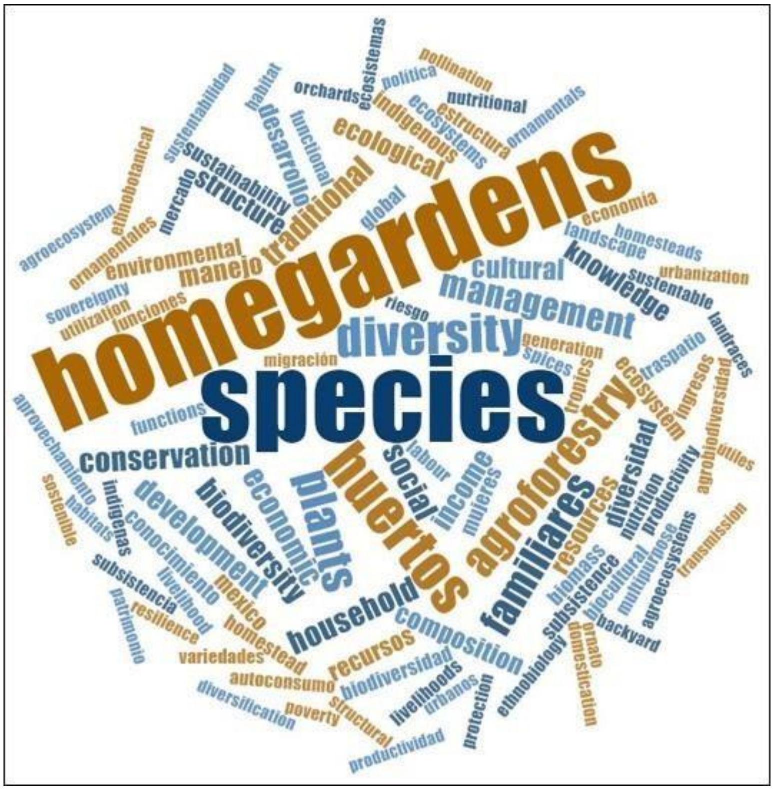

Figure 18. The word cloud of the 250 frequent words generated from the 335 publications could be distinguished based on the dominance of the word's font size.

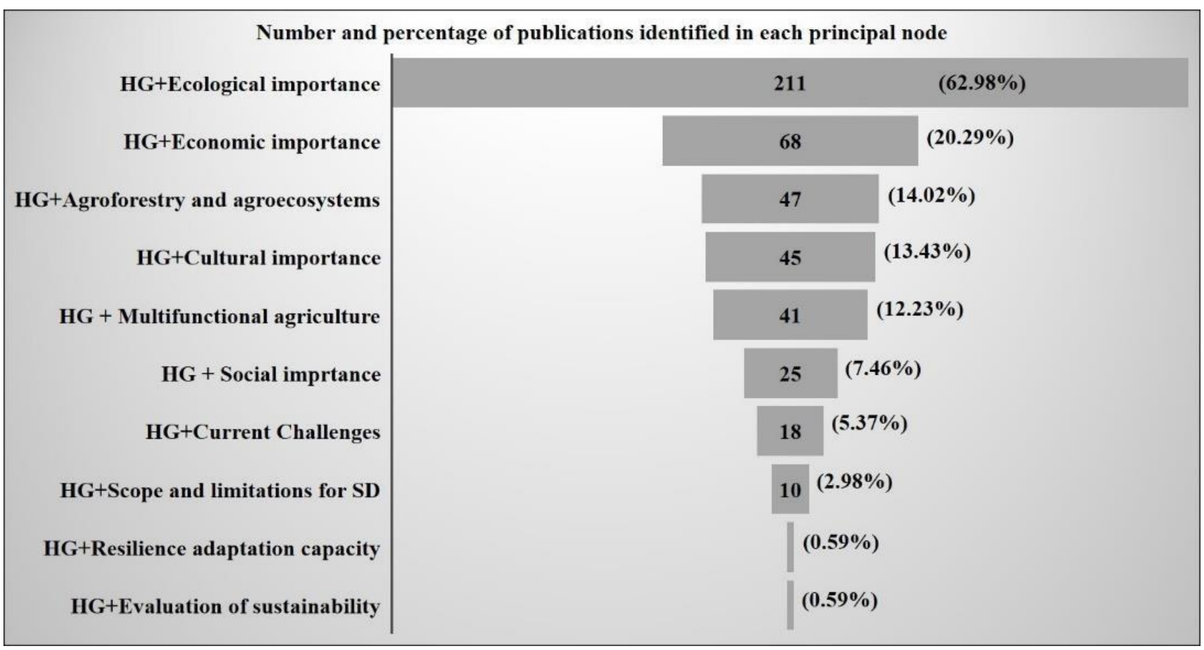

Figure 19. The number and percentage of research papers identified in each principal node determined based on keywords generated from the word frequency test.

household garden (Vasey, 1985), tropical agroforestry homegarden (Fernandes and Nair, 1986), javanese homegarden (Soemarwoto and Conway, 1992), agroforests (Kumar and Nair, 2006), and so on, which were commonly used throughout the world. However, as the term home garden is confused with ornamental garden around homes, most of the recent literature use the term homegarden to refer the land-use system (Kumar and Nair, 2006; Lope-Alzina and Howard, 2012; Rayol *et al*., 2019).

In Central and South America, names such as *solar*, *patio*, vegetable garden, fruit orchard or tropical fruit homegarden, mixed agroforestry garden, *quintais* or *quintal agroforestal*, *pomares domestics* were frequently used to refer to homegarden (Lok, 1998; Akinnifesi *et al*., 2010; Arias-Reyes, 2012; Rayol and Miranda, 2019). In Mexican rural environment, existing several regional names in the spanish language such as *traspatio* (backyard), *huerto casero* (homegarden), *huerto familiar* (family orchard), and *solar*. Also, there exist several local or colloquial names assigned by the native people that were not well documented in the literature so far (Mariaca, 2012; Duché-García *et al.*, 2017; Delgadillo and Toledo, 2018; Ordoñez Diaz *et al*., 2018a).

Regarding the concept of homegarden, some authors describe it as an integrated agroecosystem located nearby the dwelling place and usually managed with family labour to grow and produce combinations of multipurpose plant and animal species primarily for family consumption (González, 2012; Galhena *et al.*, 2013; Gutiérrez *et al*., 2015; Flota-Bañuelos, *et al.*, 2016; Garcia-Flores *et al.*, 2016a). Others define it as a less complex agroforest system with deliberate management areas of natural resources within the compounds of individual houses that not only mimics epigeal and hypogeal stratification of forest or multilayered ecosystems (Rappaport, 1971; Lope-Alzina and Howard, 2012; Chablé-Pascual *et al.*, 2015; Gbedomon *et al.*, 2015; Thomas and Ravikishore, 2017) but also fulfils different social, economic, environmental and cultural needs of the people (Torquebiau, 1992; Hoogerbrugge and Fresco, 1993; Krishnamurthy *et al.*, 2017; Rosales-Martínez *et al*., 2019).

As homegardens are man-made microenvironment within lager farming systems that includes domesticated plants, and/or animals as well as people some authors consider it as a part of an agro-socio-ecological system with high species and functional diversity (Soemarwoto and Conway, 1992; Linger, 2014; Gutiérrez *et al.*, 2015; González, 2018). According to Mariaca (2012), it is a traditional agroecosystem in which the family unit lives and carries out different agricultural production activities related to the process of selection, domestication, diversification as well as conservation of flora and fauna including fungi. Also, the HGs are one of the most important sites in which peasant families are generating, transmitting and evaluating their agricultural knowledge.

Based on the consensus of various authors, in general, the concept of the operational base of homegarden could be defined as a land-use or agroforestry system that has an intimate association with trees, shrubs, annual crops and/or domestic animals adjoining to the plots of an individual home where ecological interactions take place between an agroecosystem and the household to obtain multiple products and services mainly for the family well-being (Fernandes and Nair, 1986; Soemarwoto, 1987; Torquebiau, 1992; Kumar and Nair, 2006; Mohri *et al*., 2013; González *et al*., 2014; Cano Contreras, 2016; Duché-García *et al*., 2017; Chakravarty *et al*., 2018; Thamilini et al., 2019; Castañeda-Guerrero *et al*., 2020).

Historical development of HG

HGs are considered as one of the oldest land use activity next only to shifting cultivation practiced by our ancestors in different cultures of the world (Kumar and Nair, 2004). Historical records based on archaeological evidence or literature references suggest that HG practices seem to have arisen in prehistoric times when hunters and gatherers in their nomadic lifestyle incidentally or parallelly domesticated the wild ancestor of maize (*teosinte*), wheat, squash, and other important plants or fruit trees, at least more than 9,000 years ago (Mohri *et al.*, 2013; González, 2018).

There are many other studies across the globe approximately coincide with the above dates regarding the origin of HGs. For example, Trabanino (2018) indicates that Mesoamerican agroforestry systems such as homegardens are at least 11,000 years older. According to Miller (1992), and Miller *et al.* (2006), hunter-gatherers have occupied the western Brazilian Amazonia around 9,000 years ago and probably performed prehistoric agricultural activities adjacent to dwellings, along with or near rivers in the forest (Lathrap, 1977).

Archaeological evidence from Colombia, Ecuador, Peru, and Mesoamerica confirms that cultivation of native tubers and seed plants was taken place in Amazonia between 10,000 and 8,600 years ago (Piperno and Pearsall, 1998; Piperno *et al.*, 2000; Smith, 2001). A study from Asia (Mohri *et al*., 2013), based on the works of Hutterer (1984) and Terra (1954) indicates that, for instance, javanese homegardens originated in the 7th millennium BC, in Central Java and parts of East Java, expanding to West Java in the mid-18th century. According to Wiersum (2006), the origin of southeast Asian tropical homegardens might be around 13,000-9,000 BC.

In the case of Mexico, HG and milpa (corn, pumpkin and bean field) agroecosystems are considered as an agro-bio-cultural heritage due to its long history of about 9 millennium (González, 2018) that helped people to develop settlements with sustained annual food production (Angel-Pérez, 2013). Based on the grinding stones and botanical samples found in the state of Chiapas, Acosta Ochoa (2010, 2011) indicate that incipient or dispersed HGs were started at the end of Pleistocene epoch i.e., between 10,000-12,500 years ago. And Smith (1967), suggest that the formation of diversified homegardens (with at least nine tree species), began approximately around 6,000-7,000 BC, which was based on the evidence provided by MacNeish (1967) from the excavations carried out in the Tehuacan valley, in the state of Puebla. Also, Caballero (1992) confirms the vital role of HGs in pre-Hispanic societies such as the mayans, aztecs and totonacs continue to sustain many indigenous communities even after the colonial era. According to Fedick *et al.* (2008) traditional maya homegardens in the Yucatan peninsula dates back at least over three millennia.

Table 5. Percentage of publications in Mexico belong to each node in homegarden research.

No°	Principal nodes	No° of publications in Mexico	% of publications
1.	HG + Multifunctional agriculture (sustainable development or SD)	12	3.582
2.	HG + Ecological importance	36	10.746
3.	HG + Economic importance	17	5.074
4.	HG + Social importance	2	0.597
5.	HG + Cultural importance	19	5.671
6.	HG + Current challenges	3	0.8955
7.	HG + Scope and limitations for SD	4	1.194
8.	HG + Agroecosystems & Agroforestry	14	4.179
9.	HG + Resilience, adaptation capacity	-*	-*
10.	HG + Evaluation of sustainability	1	0.298

*(Publications not available or registered in the current study).

In summary, although the time gap suggested in different studies varies, all the above references invariably conclude that the land-use activity of HG was a millennium practice and originated due to the human perception of germination of some edible seeds or plants left incidentally in the resting places of the groups of nomadic hunter-gatherers at least more than 9,000 or 10,000 years ago.

Moreover, the transformation of the nomads from hunter-gatherer to a farmer not only contributed to establishing early human settlements where a certain plant or animal domestication were carried out adjunct to the dwelling places, primarily for subsistence, but also the development of traditional homegarden practice usually located in the surrounding areas near the individual houses.

Also, certain characteristics (such as location, species diversity, family labor and destination of the products) between prehistoric agricultural activities near early human settlements and HG systems resemble each other. In this context, considering the evidence (based on dating techniques) given by some authors like Abdoellah *et al.* (2006), Miller and Nair (2006), Acosta Ochoa (2010, 2011), Ordoñez Diaz *et al*. (2018a), González (2018), and Trabanino (2018), we could suggest that HGs could be the place where agriculture was born since the cultivation and domestication process of many species in the early human establishments influenced the development of agricultural societies in different parts of the globe. However, in general, this land-use practice has been recognized in the global arena as an important agroecosystem as well as oldest agroforestry system.

Distribution of HG

Homegardens are the most widespread use of land in the tropics and subtropics of the world, predominantly in the regions of East Africa, West Africa, South Asia, Southeast Asia, Pacific Islands, as well as Central and South America (Fernandes and Nair, 1986; Agelet *et al*., 2000; Howard, 2006; Kumar and Nair, 2006; Chakravarthy *et al*., 2017). According to Lok (1998), Rebollar-Domínguez *et al.* (2008), Mariaca (2012), Ordoñez Diaz *et al.* (2018a), and González (2018), in Mexico, homegardens are common in both rural and peri-urban areas and distributed mainly in the Central East and Southeast zones (principally in the states of Tabasco, Chiapas, Veracruz, Oaxaca, Puebla, Hidalgo and in the Peninsula of Yucatan). In general, farmers world-wide have developed these systems due to their contribution of ecosystem services which is far from negligible.

Characteristics of HG

Homegardens, in general, are distinguished among other agroecosystems due to its unique environmental, economic, social and cultural characteristics. By analyzing several documents, the current study presents the following summary of the list of general key characteristics considered by different authors across the globe to distinguish homegarden from other agricultural systems (Table 6). However, it is important to recognize that even though components of ecological environment such as geological, geographical, climatic and edaphic aspects are instrumental in determining the overall aspects of homegarden, the uniqueness of each homegarden depends mainly on cultural characteristics such as customs, traditions, individual or gender preferences of the members of the family (Smitha *et al*., 2006; Brandt *et al*., 2012; Cuevas, pers. comm., 2019). For instance, each Mexican homegardens has its characteristics that reflect the local environmental conditions as well as world vision of the native people towards the management, use and conservation of species.

Types of HG

Homegardens are generally classified based on its environmental, economic and socio-cultural characteristics or variables which mainly depend on the research focus of the study. Variables such as the area or size of the garden, climatic zones, economic conditions of the household were utilized in different studies to classify homegardens (Lok, 1998). For instance, in some parts of South Asia, gardens that contain a link to agricultural and natural landscapes generally located in rural or semi-rural areas of Sri Lanka are classified as Kandayan homegardens or forest gardens (Jacob and Alles, 1987; Perera and Rajapakse, 1991; Pushpakumara *et al.*, 2012).

In Indonesia, traditional Javanese homegardens are also referred as *pekarangan* (Wiersum, 2006). In Vietnam, diverse agri-aquacultural carried out near the domestic dwellings are distinguished as traditional integrated agriculture-aquaculture (IAA) system or *Vuon-Ao-Chuong* (VAC) system, which means Garden-Pond-Livestock pen (Trinh *et al.*, 2003). In Mesoamerica, traditional fruit homegarden that contain native fruit trees as a main component of the agroecosystem found generally near the individual home (Sotelo-Barrera *et al.*, 2016). Based on the analyses this review presents the following summary of some types of homegardens mentioned in different papers (Table 7).

Management of HG

Management of HG varies from place to place according to the ecological environment, cultural and socioeconomic contexts. As work is done manually, human labour is used as the main energy input in these traditional small-scale agroecosystems. And they do not depend on high energy inputs such as chemical fertilizers, pesticides or fuel-powered machinery. Also, very simple tools such as a small hoe, rake, spade, fork, pickaxe, watering hose and stick were used in the garden activities. Many of these tools were built from recycled material available locally. Animals such as cattle, hens found in the homegardens contributed to maintaining the fertility of the soil. Due to these reasons, HGs are generally considered as a sustainable agroecosystem from an ecological point of view. Each HG was maintained by the household members (including men, women and children) and the harvest products are primarily consumed by the family. Majority of the plants grown in homegardens are cultivated (Vogl and Vogl-Lukasser, 2003; Ángel and Méndoza, 2004; Mariaca, 2012; Chávez-García, 2012; Chablé-Pascual et al., 2015; Larios et al., 2013; Gbedomon et al., 2015; Krishnamurthy et al., 2017; Castañeda-Guerrero et al., 2020). However, some of the plants belong to other management categories: wild, tolerated, protected or fomented, and domesticated species.

Multifunctional role of HG for sustainable development

Many farmers worldwide practice HGs primarily to satisfy their family needs. However, homegardens have a good reputation for providing a series of goods and services that are not always referred to agricultural production. For example, biodiversity conservation, soil fertility, carbon sequestration, gender equity, social cohesion, savings or income from diversified biophysical outputs, and biocultural heritage conservation etc. In other words, HGs can fulfil ecological, economic and socio-cultural functions better than monocultures or other agricultural practices (Fernandes and Nair, 1986; Kumar and Nair, 2006; Lwanga, 2012; Sánchez, 2012; Agbogidi and Adolor, 2013; Mattsson *et al*., 2013; Mohri, *et al*., 2013; Calvet-Mir *et al*., 2015; Vieira *et al*., 2016; Schrader *et al*., 2017; López *et al*., 2019; Rosales-Martínez *et al*., 2019; Abdoellah *et al*., 2020; Castañeda-Guerrero *et al*., 2020). In this context, the following section intends to analyze the ecological, economic and socio-cultural importance of homegardens to have a better understanding regarding its multifunctional feature.

The Ecological Importance of HG

Recently, there is growing attention to find ways of reconciling food and agricultural production activities to confront several environmental challenges such as climate change, biodiversity loss, genetic erosion that

Table 6. Summary of the general key characteristics of the land-use system of homegardens (adapted from sources*).

No°	General characteristics of homegardens	Description
1.	Environmental characteristics	
	• Location	• Near dwelling or residence areas (which are physically delimited using fences or hedgerows or borders established through mutual understanding) (2, 3, 5, 7, 8, 11, 14) *
	• Frequency of harvest	• Daily and seasonal (2, 3, 5, 6, 14)
	• Species composition	• Resemble and mimic natural or forest ecosystems ecology (2. 6, 7, 8, 9, 13)
	• Structural complexity	• Horizontal and vertical organization (1, 3, 5, 13, 14)
	• Flow of energy	• Complex and dynamic interactions (1, 13, 14)
	• Functional diversity	• Fulfils multiple social, economic, environmental and cultural functions (1, 9, 10, 13, 14)
2.	Economic characteristics	
	• Capital investment	• Low establishment, labour and input cost (3, 8, 11, 14)
	• Income	• Main or additional income (9, 11, 13, 14)
	• Destination of products	• Family consumption (supplement or main source of living) (3, 5, 11, 14)
3.	Social characteristics	
	• Exchange of additional part-time assistance and products	• Generally, with friends and neighbours (4, 7, 8, 14)
	• Labour source	• Family labour (men, women, and children) (9, 14)
	• Access	• Easy access (8, 11,14)
4.	Cultural characteristics	
	• Selection of species type	• Based on cultural and individual preferences or needs (e.g., food, medicinal or other species) (5, 9, 14)
	• The pattern of plantation design	• Irregular (3, 5,14)
	• Type of energy	• Manual using simple hand tools (1, 5, 12, 14)
	• Type of technology	• Simple technology varies according to the world vision of each culture (1, 5, 13, 14)
	• Degree of management	• Wild, tolerated, fomented, cultivated and domesticated (15)

*Sources: 1. Rappoport (1971), 2. Barrera *et al*. (1977); 3. Ruthenberg (1980); 4. Fernandes and Nair (1986); 5. Niñez (1987); 6. García-Flores *et al.* (2016a); 7. Soemarwoto and Conway (1992); 8. Hoogerbrugge and Fresco (1993); 9. Lok (1998); 10. Mendez (2000); 11. Mitchell and Hanstad (2004); 12. Wiersum (2006); 13. Kumar and Nair, (2006); 14. Galhena *et al*. (2013); 15. Larios *et al*. (2013) and Angel-Pérez (2013).

Table 7. Summary of the types of *homegarden* (adapted from different sources*).

No°	Variables or criteria	Types of homegarden
1.	Total, area or size of homegardens	Big or medium or small (5, 8, 9, 11)
2.	The economy of the household	Survival, subsistence, market and budget gardens (5, 10, 12, 14) *
3.	Distribution of homegardens based on:	
	• Ecological zone	• Tropical or temperate (5, 9, 14)
	• Geographical zones	• Rural or peri-urban or urban (5, 9)
4.	Purpose of production activity	Subsistent or semi-commercial or commercial (13)
5.	Species diversity	
	• Species (density) diversity	• High or low diversity (1, 2, 3, 6, 7, 8, 9, 10, 11, 13)
	• Management zones	• Mixed management zones of plants (medicinal, vegetable, ornamental, etc.) and trees (multi-purpose) including habitation areas (8, 9, 10, 13)
6.	Structural diversity (space utilization or division based on management areas)	• Multi-strata homegardens or agroforests (1, 3, 4, 5, 8, 9, 13)
7.	Functional diversity	• Fruit, vegetable, ornamental, handcrafting and mixed production gardens (4, 7, 10, 14)

*Sources: 1. Rappoport (1971), 2. Barrera *et al*. (1977); 3. Ruthenberg (1980); 4. Fernandes and Nair (1986); 5. Niñez (1987); 6. García-Flores *et al.* (2016a); 7. Soemarwoto and Conway (1992); 8. Hoogerbrugge and Fresco (1993); 9. Lok (1998); 10. Mendez (2000); 11. Mitchell and Hanstad (2004); 12. Wiersum (2006); 13. Kumar and Nair, (2006); 14. Galhena *et al*. (2013).

affects human well-being. In this context, traditional homegardens have attracted considerable attention of scientists and developmental strategists due to its potential to provide multiple benefits as well as to contribute to achieving environmental sustainability. During the past few decades, many studies demonstrate the ecological importance of HGs by analyzing its: a) species diversity, b) structural diversity, and c) functional diversity.

a) Species diversity

The composition of HG refers to both biotic and abiotic elements found within the system (Lope-Alzina and Howard, 2012). However, several authors from a wide range of disciplines (ethnobotany, agroecology, anthropology, agroforestry, ethnoecology) principally focus on the richness, frequency, dominance and abundance of plant and animal components in the study of homegardens. Most of the studies demonstrated the high floristic composition of HGs by inventorying species and concluded that HGs are one of the agroforestry or agroecosystems that consists of highly diversified multipurpose species located around homesteads (Fernandes and Nair, 1986; Miller and Nair, 2006; Kabir and Webb, 2007; Kumar, 2011; Rayol *et al*., 2017). Regarding the origin, HGs also consists of many non-native species that varied according to the history (particularly trade) of the region.

Moreover, the potential value of HGs as repositories of biological diversity to conserve many landraces and cultivars, as well as wild and endangered species is recognized worldwide (Watson and Eyzaguirre, 2002; Galluzzi *et al*., 2010; Avila *et al*., 2017). For instance, more than 301 trees and shrubs were reported from the Mayan homegardens of Yucatan, Mexico (Rico-Gray *et al*., 1990, 1991), 419 species belonging to 109 families were reported in Bangladesh (Kabir & Webb, 2007), 186 plant species in the North-East Brazilian urban and suburban homegardens (Akinnifesi *et al*., 2010); 223 plant species with different uses were identified in Campeche, Mexico (Flota-Bañuelos *et al*., 2016), about 357 species belonging to 263 genera and 102 families were found in Totonac homegardens in the state of Puebla, Mexico (Castañeda-Guerrero *et al.*, 2020).

However, as HG is a dynamic system with constant changes, the estimated data of species richness in various studies depends mainly on the selected sample size or methodological procedures and variables. For instance, as more HG units are surveyed, high diversity will be reported. Besides, as limited plant specimens were collected to identify their taxonomical characteristics, it is unclear whether standard inventorying procedures were considered to avoid enlisting same species into different ones due to the complication involved in distinguishing between many varieties and local names.

Some studies also analyzed the correlated factors that influence plant species diversity in homegardens. Although personal preferences of the members of the family is the key factor to determine the floristic composition of HGs, a broad range of other variables related to ecological conditions, cultural demands and socioeconomic context also influenced the crop diversity of HGs. For example, a study conducted at a global scale (Padulleés *et al*., 2014) indicates that mean temperature, potential evapotranspiration, the distance between settlements and differences in GDP (Gross Domestic Product) per person, are some important variables that explain the taxonomic dissimilarity between gardens.

Other variables such as population density, garden type, mean annual rainfall, and dominant language of the family also contribute positively (but lesser than above variables), to the species diversity in HGs. Housing or farming age and size (Eichemberg *et al*., 2009) education, gender, homeownership (Yabiku *et al*. 2008; Larson *et al*., 2009; Zhou *et al*., 2009) are some other factors that have a significant influence in determining the types of plants grown by people in their gardens.

Other studies apply the diversity index methods to evaluate the alpha, beta and gamma diversity in HGs. However, in general, most of the HG research that intends to evaluate the role of agrobiodiversity primarily focus on interspecific (variation between species) diversity of plant and animal components, and there is a lack of adequate data analysis on intraspecific (variation within species) diversity.

According to Cuevas (pers. comm of the second author), the comprehensive assessment (not just the measurement) of the existing agrobiodiversity in an agroecosystem (among them the family gardens), requires adjusting the methods (such as Shannon and Simpson index) used to date, since, in this case, the concept of species is insufficient, being essential to consider the infraspecific variants (cultivar, subspecies, race, cultivar). And even within these, those of cultural importance such as flavour, pungency, as well as agronomic importance as susceptibility to Phyto pathological or environmental problems such as resistance to drought should be considered to determine the exact status of agrobiodiversity in a zone.

Regarding fauna, very few domestic species such as chicken, pig, cattle, sheep and goats, dominate the scenario in the HG system and the role of wild or semi-domesticated species also needs to be focused on the research (Ruíz-Nieto *et al*., 2019). Besides, there is not enough research that analyzes the importance of other living components that is associated with agrobiodiversity of homegardens such as fungi and microorganisms (bacteria, algae, lichens, insects etc.).

Moreover, as the potential use of many wild species within HGs have only begun to be documented, further research from ethnoecological and ethnobotanical approaches are required to identify the plant and animal resources to implement a win-win strategy in tackling both livelihood challenges as well as sustainable development constraints.

b) Structural diversity

The structure of HG refers to the spatial organization of all elements within the system. In other words, both horizontal (livestock, buildings, vegetation) and vertical (vegetation) distribution of system's components combine to form the full structure of HG (Rappaport, 1971; Lok, 1998; Lope-Alzina and Howard, 2012; Thomas and Ravikishore, 2017). Many studies are given more emphasis to analyze the vertical strata of HG due to the complexity of its functional dynamics. For example, the vertical height of the vegetation (predominant) component determines the type of interactions (complementary or competitive) among species and allow a good utilization of environmental factors such as sunlight, water and nutrients. A study from India, suggests that existing facilitative mechanism by the main crop (coconut trees) to its intercrops (clove and nutmeg) above the ground, but exploitative mechanism below the ground (Pandey *et al*., 2014).

Also, it has been generally recognized that vertical (height) strata of HGs have the multi-strata or multi-storey pattern (similar to that found in natural ecosystems or forests) with a combination of various plant species of different life forms and heights distributed in different niches (Kumar and Nair, 2006; Pandey *et al*., 2014; Castañeda-Guerrero *et al*., 2020). For instance, according to Fernandes and Nair (1986), Caballero (1992), Lope-Alzina and Howard (2012) most of the HGs are distributed vertically at least with three layers: lower with herbs and food or medicinal plants (0-2 m), intermediate with shrubs or bushes and young low trees (3-5 m) and upper with tall trees (5-10 m). Other studies identified four (Krishnamurthy *et al*., 2017) and six (De Clerck and Negreros-Castillo, 2000) different vertical strata in Mayan-Yucatecan homegardens in the state of Quintana Roo in Mexico.

The horizontal base structure of HGs is characterized by identifying areas with specific use and management that frequently resembles the worldview or cosmos of native people. For example, some areas or zones covered with ornamental, herbs, perennial trees or shrubs, annual crops, uncultivated plants, buildings or dwelling space (Caballero, 1992; Lok, 1998; Mendez, 2000; Lope-Alzina and Howard, 2012).

Furthermore, like species diversity, the structural diversity of homegarden also varies from place to place according to the local ecological, socioeconomic and cultural characteristics. Planting pattern, design and choice of the plants, for example, influence significantly the structural pattern of HGs. According to Vibhuti *et al.* (2018), altitudinal variations and size of HGs determine the planting pattern and plant choices or preferences which in turn are highly linked to aesthetic or cultural values of the HG owners.

In summary, the structural complexity of HG systems has been claimed to play a pivotal role in providing several ecological services and functions. For example, the structural diversity of agroecosystems reducing the risk of crop failure, providing shade to understory plants, protecting soils from erosion or degradation due to heavy rain or wind, increasing the efficiency of resource management and its resilience, etc. (Soemarwoto, 1987; Abdoellah *et al*., 2006; Vlkova *et al*., 2011). However, as it is difficult to separate the species-specific interactions due to the structural complexity of HGs, very few studies intend to understand its mechanism of interactions or the flow of energy in below and above ground (Rappaport, 1971). Also, the functional structure of HGs is not given enough focus to understand well (Wiehle *et al*., 2014). Therefore, more research should focus the functional dynamics of homegardens based on its structural diversity to understand the complexity involved in it to improve the mechanisms of these systems in near future.

c) Functional diversity

HG systems provide a series of advantages in terms of ecosystem services by fulfilling diverse environmental, socio-economic and cultural functions. As the role of economic and socio-cultural importance of HGs are discussed below, this section explores about some ecological functions. For instance, HGs as one of the sustainable family farming system improve fertility and conserve the soil which is the basis for agriculture and forestry production. A study to evaluate the soil chemical properties of homegardens from Eastern Amazon, Brazil concludes that these systems act similarly as the secondary forest in terms of nutrient cycling and conserve the fertility of tropical soils. Thus, it could be recommended as one of the alternative strategies to restore degraded areas (Thiago *et al*., 2016).

Other studies acknowledge that HG systems serve as a reservoir of genetic diversity, thereby well suited for *in situ* (maintenance of populations in natural surroundings) and *circa situm* (maintenance of populations within altered agricultural landscapes or farm) conservation of potential wild or endangered species for the present as well as future use (Kumar *et al*., 1994; Akinnifesi *et al*., 2010; Galluzi *et al*., 2010; Agbogidi and Adolor, 2013). According to Schrader *et al*. (2017), HGs ensure pollination services through the conservation of species richness and abundance of wild bees which are essential to secure farmers yield of many crops.

Many studies highlighted the potential role of HGs to reduce the global warming by serving as a reservoir of short- and long-term stored carbon in its soil, wood products and vegetation biomass (Saha *et al*., 2009; Mattsson *et al*., 2014; Subba *et al*., 2017; Marambe *et al*., 2018). Some studies showed how the practice of homegardens help to reduce the local rate of deforestation by diminishing the family's livelihood dependency on forest-based products such as firewood, timber, fiber, medicine, animal fodder and shade (Albuquerque *et al*., 2005; Das and Das, 2005; Kehlenbeck *et al*., 2007). Also, HGs provide essential regulating services such as pest regulation, water and nutrient cycling, erosion control.

In general, HGs improve local environmental or climatic conditions and act as a refuge to wildlife as well as provide comfort and security to the family. Moreover, it adds value to the entire landscape as well as to the property itself (Galhena *et al*., 2013; Idohou *et al*., 2014). However, very few studies provide quantitative data regarding the functional dynamics of this complex agroforestry system. Also, the functional equivalence or redundancy (i.e., multiple species representing a variety of taxonomic groups can share similar, if not identical, roles in ecosystem functionality, for example, nitrogen fixers) suggested by Salmerón *et al*. (2017), should be considered in the future research of this ancient land-use practice.

Moreover, it is not well known whether the knowledge of the local people associated with HG practice is still transmitted to the next generation to improve its resilience in the face of current challenges. This is why it is important to understand that although it is essential to measure the so-called biocultural heritage that a peasant family has inherited, it is equally important to consider the degree of appreciation for it, which is evidenced in its daily application.

The Economic importance of HG

Several studies recognize that HGs as a source of edible fruit, vegetables, medicines and other products that satisfy many human needs as well as provide food and nutritional security of the owner´s family in different parts of the world. For example, according to (Torquebiau, 1992), in many tropical developing countries, over one-third of the total calories and protein consumption were obtained from the food production of HG systems. Thamilini *et al*. (2019), concludes that families with organized HGs had achieved greater nutrient adequacy by means of higher dietary diversity. Furthermore, it plays an important role in the subsistence economy of the peasant´s families, as the harvest products from HGs either reduce the personal consumption expenses or provide additional or supplementary cash income by selling them in the local market. Sometimes exchanging the production of HG products with the owner's friends and neighbours without ready cash or money also help to save money or labour (Blanckaert *et al*., 2004; Cámara-Córdova, 2012).

Besides, HGs are profitable ventures from the ecological point of view, as many benefits or positive externalities (such as erosion control, carbon sink) of HGs cannot be evaluated using conventional economic approaches such as yield, cost-benefit analysis and net present value (Torquebiau and Penot, 2006). For these reasons, HGs are an effective approach to enhance the livelihood as well as the economy of the people who depend on it.

However, HGs contribution of economic benefits primarily depends on the plants or species that are grown according to the satisfaction of the needs and requirements of the owners of the households. For example, changes in the demand of the market significantly influence the owner's choice of the production as well as its destiny i.e., whether for self-consumption or commercial purpose (Peyre *et al*., 2006). Moreover, without diversifying the horizontal and vertical structure of HGs, profit enhancement cannot be expected.

In other words, as each homegardens are structurally and functionally different from each other, it is important to diversify and add value to HG products to generate income as well as food and nutritional security (Thomas and Ravikishore, 2017). Besides, as the value of many goods and services are difficult to quantify, the amount of income and savings derived from these systems are not exactly presented in many papers.

Therefore, more research is needed to identify the influence of current local trends or societal pressures over the owner's choice of HG management as well as structural diversification of specialized HG systems to increase economic benefits. Moreover, assessment of the nutritional value of each native species and the evaluation of food security based on access, availability, utilization and market (the four pillars of food security) in different regions, especially among indigenous groups are recommended for further research.

The socio-cultural importance of HG

Notable studies acknowledge that HG is a social capital that not only ensures the availability of multiple products but also develops social interactions with neighbours and relatives which in turn strengthen the relationship between them. It also reflects the societal status of the owner by increasing stability as well as the integrity of the households through continuous food supply employment and supplementary cash income throughout the year. Especially, during crisis periods (such as wars, conflicts, natural hazards, pandemic), HGs not only guarantee basic comfort and food security but also act as a safety net in providing alternative livelihood sources to the family (Kabir and Webb, 2008; Buchmann, 2009; Agbogidi and Adolor, 2013; Linger, 2014; Bargali, 2016).

Moreover, HGs are considered as a valuable patrimony to the native people, as it keeps alive the cultural history as well as local knowledge about species management, use and conservation from generation to generation. That's why, it is recognized as a biocultural heritage that reflects the world vision or cosmos of the local indigenous population who experimented and transmitted their knowledge of selection and domestication of plant and animal species over generations (Boege, 2008; Mariaca, 2012; Calvet-Mir *et al.*, 2015).

However, although some of these studies focus on sociocultural aspects of HGs, none examines how changes in these aspects impact homegarden systems resilience. Hence, in future, the information regarding sociocultural factors needs to be evaluated then interpreted with caution as they have a significant influence in the variations of the structure and species composition of homegardens as well as management practices, which in turn system's sustainability criteria.

Current status and challenges of HG

Several studies highlight considerably that the millennial practice of homegarden design is the most important component of traditional agroforestry or agroecosystem in many parts of the world, particularly among indigenous people living in rural communities of Mexico. It is also recognized as a multifunctional land-use system that provides numerous (ecological, economic, and socio-cultural) benefits to enhance the livelihood of the local native people throughout the year.

Recently scientists, as well as strategists of developmental programs around the globe, are refocusing their attention towards HGs due to their sustainability and multifunctional role. However, despite worldwide recognition of the importance of HGs, currently, this ancestral practice is confronting enormous challenges. For instance, challenges such as agricultural expansion and fragmentation, climate change, loss of biodiversity, cultural erosion, socioeconomic trends have a significant influence in the future transformation of traditional agroecosystems, particularly homegardens. Even though HG practice have evolved over centuries and survived too many changes until now, however, the agrodiversity associated with these systems remains uncertain.

Many authors have already expressed their concern about the future of this traditional practice. To be specific, questions are already raised whether the shift from subsistence to market-oriented agriculture, rural migration either in pursuit of education or labour, land pressure due to urbanization, lack of interest of the new generations to care the traditional farming systems due to the rapid changes in the pattern of food, environmental and livelihood conditions etc. are threatening the very existence of HGs, particularly at the local scale (Kumar and Nair, 2006; Boege, 2008; Mohri *et al.*, 2013; Vogl-Lukasser and Vogl, 2018).

On one hand, modifications in the fundamental structure and functions of the HG system due to above challenges not only compromise its potential (multifunctional and sustainable) role, but also the invaluable biocultural knowledge involved in it. On the other hand, many people in different parts of the world who practice HG are still living under poor conditions and lot of them are forced to abandon this practice in search of alternative options for their livelihood mainly due to the impact of above-mentioned changes. Particularly, the new generations are turning their backs to homegarden practice due to the increasing economic pressure and changes in their lifestyle. Besides, the importance of this inherited practice through different generations is still underestimated and neglected in many places, especially in Mexico (Eichemberg *et al.*, 2009; Mariaca, 2012; Ordoñez Díaz *et al.*, 2018b).

The above-mentioned status of HG is mainly due to the lack of local government policies or programs to reevaluate and implement HG practice by diversifying or adding value to the products. Also, encouraging owners of the homegardens to manage and conserve this traditional land-use practice by offering economic incentives or payment for environmental services. In this context, there is an urgent need to stimulate more policies to promote HG as one of the alternative strategies to contribute to achieving the dual goals of sustainable livelihood and environment. Also, the capacity of the HGs to confront current challenges, as well as its sustainability, should be reassessed. However, in situations such as the current pandemic of Covid-19, these systems have become very necessary to achieve food security as well as food sovereignty for millions of people.

Summary of the research gaps & perspectives in the field of HG

Based on the extensive literature analysis this study highlights that although several investigations on HGs have been conducted by a wide range of disciplines in different parts of the globe in the past few decades, there exist many gaps that need to be focused on the future. Most of the HG studies around the globe were conducted intensively in the tropical zone, and scientific data on temperate and semi-arid homegardens are scarce. Most of the investigations until now either describe the biophysical aspects of HGs or analyze the functions based on its ecological attributes such as structure and composition in the selected study area.

Although species diversity in HGs has been extensively inventoried, there is a substantial lack of quantitative data about intraspecific diversity a very important aspect related with the ethnoresource concept involved in the agrobiodiversity as part of the HG. Moreover, the results of interspecific diversity may have biased due to the variations in the selected criteria to assess the species richness. Experimental data evidence still needs to be gathered regarding the role of associated agrobiodiversity (for instance, soil organisms or bees or birds) in the HG systems.

Besides, quantitative data on biogeochemical processes such as the mechanism of nutrient cycling, carbon and water flux, species-specific interactions of above as well as below ground within the system have not been sufficiently addressed up to now. Also, research about the functional equivalence or redundancy of HGs is lacking. As there are very few papers that focus the economic and socio-cultural aspects of HG, future research should assess carefully the positive externalities using alternative socioeconomic approaches from the ecological perspective. And data evidence regarding geographical and regional level comparison as well as extent and distribution of HG practice are still lacking.

Besides, there are fewer investigations that use the holistic approach to figure out the variations and dynamics of this complex agroecosystem. It is also surprising that there is a lack of research to assess the capacity of these systems to resist and adapt current ecological, economic and socio-cultural changes. In this context, the degree of sustainability of HGs based on its resilience towards current challenges needs to be examined using holistic as well as ethnobotanical approaches. As the main intention of this review is to identify the scope and limitations of HG research in Mexico, we infer that the global scenario about the current status as well as gaps and perspectives of HG research also applies to Mexico. Although notable studies were conducted in Mexico, still more interdisciplinary and transdisciplinary research on HG is needed.

Limitations of the current review

Although the main conclusions of this review remain robust, there are some limitations in the current study. An exhaustive literature review was conducted to analyze the current status of homegardens around the world, especially in Mexico. Although there are numerous published documents (including grey literature such as a thesis) in the HG research, we considered only those papers found in the initial results based on the search criteria mentioned earlier. As publications from all geographical and climatic regions were not considered in the present study, the results of this review may not be sufficiently precise.

Also, some research papers referred here were not codified in the current NVivo analysis due to the following two reasons: 1) some of them were not available due to the inaccessibility in the free public search domains, and 2) some papers were found in the later specialized search using some specific keywords to rationalize certain arguments. For example, to analyze the origin and characteristics of HGs. Moreover, regarding the variables used in this review, some of them were selected to match the appropriate pre-determined categories and therefore this classification may be incomplete. Additionally, the results of the word frequency test varied widely based on the applied criteria, which may have biased the results to some extent.

CONCLUSIONS

Many scientists and developmental strategists from different parts of the globe concur that the ancestral practice of homegardens guarantees a low-input sustainable agricultural production without major environmental consequences than other farming systems. Also, it is a multifunctional land-use system that continues to meet the internal needs of the family as well as safeguard agrodiversity. Moreover, it is recognized as a biocultural heritage site, and therefore a valuable patrimony to humanity.

However, despite its potential role to contribute to sustainable development, the current environmental, socioeconomic and cultural challenges are threatening the very existence of HGs. Hence, there is an urgent need to stimulate local government policies to implement and promote HG as a win-win solution to achieve the dual goals of sustainable livelihood and environment.

Besides, although advances made in the HG research worldwide during the past decades, yet there are several research gaps mentioned in the earlier section needs to be focused on the future. Particularly, there has been less research emphasis on measuring agricultural sustainability of HGs from holistic as well as ethnobotanical perspective. Besides, there is a substantial lack of quantitative data about its degree of resilience and sustainability to confront current changes.

As HGs are the most complex and dynamic system compare to monoculture, no proper and widely applicable methodologies are yet available to examine the resilience attribute to evaluate its degree of sustainability for drawing suitable inferences. All the above inferences also apply to Mexico. Thus, it is essential to figure out immediate actions to enhance the resilience of homegardens to confront emerging challenges as well as to conserve the epitome of HGas a valuable patrimony to future generations.

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4. ANALYSIS OF THE DIVERSITY OF SPECIES, STRUCTURE AND FUNCTION OF TOTONAC HOMEGARDENS IN PUEBLA, MEXICO*

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Director: Dr. Jesús Axayacatl Cuevas Sánchez.

Analysis of the diversity of species, structure, and function of Totonac homegardens in Puebla, Mexico

Abstract

Given the limited availability of information about the agrobiodiversity of traditional agroecosystems in Mexico, the current study analyzes the diversity of species, structure and function of Totonac homegardens in the Santiago Ecatlan community, Puebla. Data were collected from twelve homegardens during June 2018-July 2019. Semi-structured interviews, ethnobotanical exploration, and participant observation were employed. Plant species diversity was estimated using the PAST 4.0 program. A total of 101 plant species belonging to 45 families and 93 genera were recorded. The maximum values logged were in homegarden N°1, with a plant species richness of 49 and a Shannon Diversity Index of 3.697. The minimum values were found in homegarden N°11, with species richness of 20, and a Shannon Index of 2.863. Five species of domesticated animals belonging to four families and five genera were recorded. The maximum value of edaphic macrofauna was found in homegarden N°1 with 1800 individuals/m^2, and the minimum value in N°4 with 100 individuals/m^2. The vertical structure in all homegardens consisted of four layers, and the horizontal ranged from four to seven management zones. A total of 13 use categories were identified, of which ornamental, food, and medicinal were dominant. The high diversity of species, structure, and functions in Totonac homegardens highlights the importance of promoting them as a biocultural heritage to preserve agrobiodiversity and cultural identity.

Keywords: agrobiodiversity, agroecosystems, ecosystem services, indigenous knowledge, sustainable agriculture

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Análisis de la diversidad de especies, estructura y función de los huertos familiares Totonacos en Puebla, México

Resumen

Dada la disponibilidad limitada de información sobre la agrobiodiversidad de los agroecosistemas tradicionales de México, el presente estudio analizó la diversidad de especies, estructura y función de los huertos familiares totonacos en la comunidad de Santiago Ecatlán, Puebla. Se recogieron datos de doce huertos familiares entre junio de 2018 y julio de 2019. Se emplearon entrevistas semiestructuradas, exploración etnobotánica y observación de los participantes. La diversidad de especies de plantas fue estimada usando el programa PAST 4.0. Se registraron 101 especies de plantas pertenecientes a 45 familias y 93 géneros. Los valores máximos registrados fueron en el huerto N°1, con una riqueza de especies vegetales de 49, y un Índice Shannon de 3.697. Los valores mínimos se registraron en el huerto N°11, con una riqueza de especies de 20, y un Índice de Shannon de 2.863. Se registraron cinco especies de animales domésticos pertenecientes a cuatro familias y cinco géneros. El valor máximo de la macrofauna edáfica se encontró en el huerto N°1 con 1800 individuos/m^2, y el valor mínimo en el N°4 con 100 individuos/m^2. La estructura vertical en todos los huertos familiares consiste en cuatro estratos y la horizontal osciló entre cuatro y siete zonas de manejo. Se identificaron un total de 13 categorías de uso, de las cuales las ornamentales, alimenticias y medicinales fueron las dominantes. La gran diversidad de especies, estructura y funciones de los huertos familiares totonacos pone de relieve la importancia de promoverlos como patrimonio biocultural para preservar la agrobiodiversidad y la identidad cultural.

Palabras clave: agricultura sostenible, agrobiodiversidad, agroecosistemas, conocimiento indígena, servicios ecosistémicos

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Introduction

Agrobiodiversity is an essential element for the sustainability of agroecosystems and food systems (Biodiversity International, 2017; Zimmerer & Haan, 2017), defined as the diversification of plants, animals, and micro-organisms that are used directly or indirectly for food or agriculture production (Food and Agriculture Organization of the United Nations [FAO], 1999). However, current global challenges such as increasing population growth, land-use change, anthropogenic climate change, rural migration, agricultural and food homogenization increase the risk of agrobiodiversity loss at different spatial scales (FAO, 2019). Furthermore, acculturation processes significantly increase this risk by hindering the transmission of knowledge about agricultural biodiversity as part of one's biocultural heritage (Boege, 2008).

To confront this scenario, there is an urgent need to design and implement strategies to conserve existing agrobiodiversity levels as well as recreate lost agricultural richness worldwide. Thus, assessing the status of agrobiodiversity at global, regional, and local scales is a fundamental step toward integral conservation. Mexico is one of the most important countries worldwide to study agrobiodiversity as it is the center of origin, domestication, and diversification of many species with both national and global importance (Khoury et al., 2016). This is also reflected in its many agroecosystems, which are possible thanks to its high levels of agricultural diversity and the multiple types of climates, relief, soil, and culture within the country.

One of these agroecosystems worthy of in-depth study is the homegardens, which are characterized by high agrobiodiversity that provides food and fulfills multiple functions or ecosystem services. Homegardens are generally described as an integrated agroecosystem located near a residence and usually managed by family labor to grow and produce a combination of multipurpose plant and animal species primarily for family consumption (Lok, 1998; Galhena, Freed, & Maredia, 2013; García-Flores, Gutiérrez-Cedillo, Balderas-Plata, & Araújo-Santana, 2016). The diverse land-use system of homegardens not only imitates natural forest ecosystems (Caballero, 1992; Kumar & Nair, 2004) but acts as a vital repository of plant and animal genetic resources. Additionally, it represents *in situ* conservation of wild and cultivated species as well as an essential place for knowledge transfer and exchange (Albuquerque, Andrade, & Caballero, 2005: Galluzzi, Eyzaguirre, & Negri, 2010).

Most homegarden studies in Mexico either describe their biophysical aspects or analyze their functions based on ecological attributes such as structure and composition in the selected study area. Although species diversity in homegardens has been extensively inventoried, there is a substantial lack of quantitative data regarding the current status of agrobiodiversity among different cultural groups, especially in the Totonacapan region in the State of Puebla. Given this knowledge gap, the objective of this research was to analyze the status of agrobiodiversity of Totonac homegardens in the community of Santiago Ecatlan, in the State of Puebla, Mexico. There are different levels (e.g., diets, agricultural systems, and genetic resources) at which agrobiodiversity can be understood. However, this paper focused on the diversity of species, structure, and function in the selected study units.

Materials and methods

The study was conducted in Santiago Ecatlan in the municipality of Jonotla, in the State of Puebla, Mexico (figure 20). This community belongs to the Totonacapan region, dating back to around 1150 B.C (Pascual, 2006). It was chosen because of its long tradition of homegardens, which have been prevalent among the indigenous Totonac people for many generations. The region can be found between the parallels 20°00′ and 20°10′ North latitude; meridians 97°27′ and 97°36′ West longitude; with an elevation between 550 and 680 m a.s.l, and the municipality of Jonotla at an elevation between 100-1100 m a.s.l.

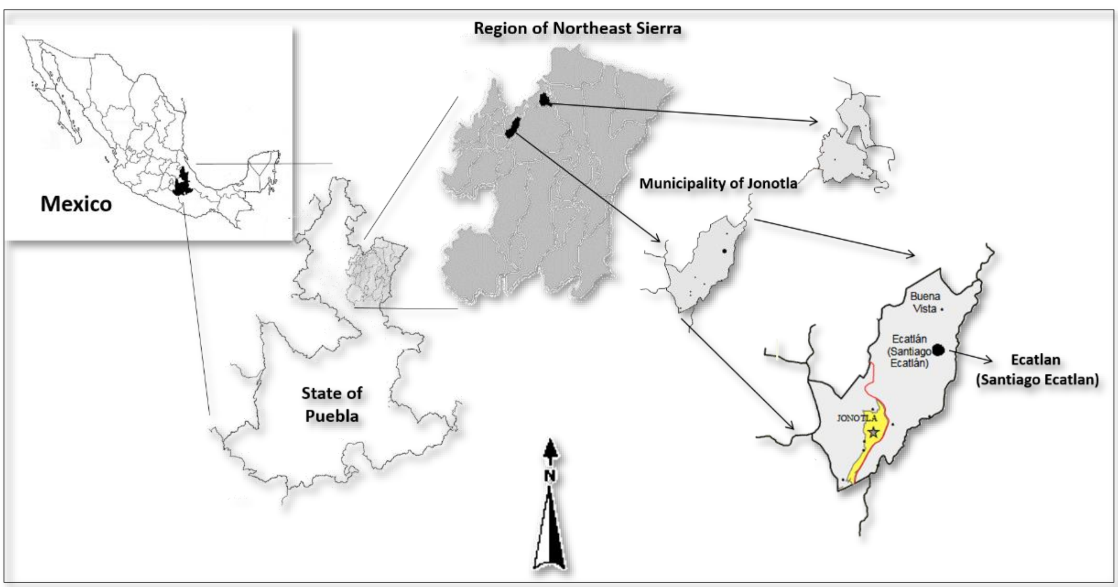

Figure 20. Map of the study area showing the location of Municipality Jonotla in the State of Puebla, Mexico
Source: Adapted from INEGI (2020)

The average annual temperature is 26 °C, and it has an average yearly rainfall of 4100 mm. According to García (2004), the symbols for this climate are A(C) (w) i' g (i.e., a warm climate that tends to be temperate, with a rainy season in summer, slight temperature oscillation, and an annual march of the Ganges type temperature). According to INEGI (National Institute of Statistics and Geography, 2009), the type of soil that predominates in the study zone is Leptosol (47.70 %), Regosol (36.88 %), Phaeozem (7.94 %), and Andosol (5.09 %). The primary type of vegetation is the High Perennial Forest. Due to the presence of high biological diversity found in Mesophilic Mountain Forests and High Perennial Forest, CONABIO (National Commission for the Knowledge and Use of Biodiversity) located this area within Priority Terrestrial Regions (RTP) of Mexico as RTP 105 (Arriaga et al., 2000). Most of the territory has coffee plantations and reduced areas of cultivated pasture, and even smaller spaces where corn, beans, amaranth, peanuts, and vanilla are grown.

Data was collected between the period of June 2018-July 2019. Considering the complexity of this research, both qualitative and quantitative methods were applied to gather the data sets and to perform their analyses. A total sample of 12 homegardens was selected in Santiago Ecatlan based on the criteria of schedule availability and willingness to participate in the research process. Participants were initially enlisted using the snowball method of non-random sampling. From the selected households, a total of 25 members participated in the current study, of which 9 were men and 16 women, ranging in age from 21 to 90 years old.

A wide range of information relevant to the structure, composition, diversity, and function of homegardens was collected using different qualitative research techniques, based on the approach found in Hernández (1970). A plant inventory was taken based on an ethnobotanical exploration while walking in the garden. Participant observation and semi-structured interviews comprised of both closed and open-ended questions relevant to the management, use, and conservation of resources were performed with the family members of each household. Participants identified plant names during the field walkthrough, which were later confirmed via a literature review. Any unconfirmed plant specimens were photographed in their habitat for later identification by plant taxonomy experts at MEXU UNAM National Herbarium in the State of Mexico.

To collect macrofauna samples, the standard line transect method of the International Program of Biology and Fertility of Tropical Soil (TSBF) was followed by studying soil monoliths of 25x25x30 cm and the extraction of the fauna manually *in situ* (Anderson & Ingram, 1994; Cabrera et al., 2017).

Data analysis was conducted using different quantitative methods. A Microsoft Excel spreadsheet was used to systematize the collected ethnobotanical data. Species abundance was estimated via the total number of individual plants of each species per homegarden. Species frequency was calculated by the number of individual plants of a species with respect to the total number of individual plants in the homegarden. The Diversity Index of the software program of PAST (Paleontological Statistics Software Package for Education and Data Analysis) 4.0 (Hammer, Harper, & Ryan, 2001) was used to calculate plant species richness, diversity, and dominance value of each homegarden (table 8). Specific richness was computed using the Margalef Diversity Index. Diversity was calculated using both the Shannon-Wiener and Simpson Index. Moreover, the representativeness was calculated using the Simpson Dominance Index. Also, the equity, or the proportion of the observed diversity for the maximum diversity expected, was computed using Pielou Index.

Table 8. Distinct indices utilized in the analysis of plant species diversity in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

Name of Diversity Index	Equation
Species richness (S)	Species richness was determined as the total number of species per homegarden.
Margalef Diversity Index ($\boldsymbol{DMg}$)	$$DMg = \frac{s-1}{ln\,N}$$ Where: S= Total number of species in the study unit or sample; N=total number of individuals of all species; ln=natural logarithm.
Shannon-Wiener Diversity Index ($\boldsymbol{H'}$)	$$H' = -\sum_{i=1}^{s} p_i Inp_i$$ Where: S=total number of species (richness) in the sample; p_i=the proportion of S made up of the i^{th} species. In=natural logarithm of p_i.
Simpson Dominance Index ($\boldsymbol{\lambda}$)	$$\lambda = \sum_{i=1}^{s} \left(\frac{n_i(n_i-1)}{N(N-1)}\right)$$ Where: S= total number of species; n_i=the total number of individuals of the n^{th} species; N=the total number of individuals of all species.
Simpson Diversity Index (D)	$$D = 1 - \lambda$$ Where: λ = Simpson Dominance Index.
Pielou Index (J)	J=H'/H'max Where H'=diversity; H' max= maximum diversity, i.e., ln (S) and S= number of species in a sample.

Source: Adapted from Moreno (2001)

Results

Species diversity of flora

A total of 101 plant species belonging to 45 families and 93 genera were recorded in the study units (appendix 1). Forty-one species were native to the region, three of which were endemic, and 60 were introduced. Twenty-one families dominated the diversity of flora in the study area. The Solanaceae, Fabaceae, and Euphorbiaceae families covered around 5.94 % of the diversity count, each with six species, followed by the Lamiaceae, Poaceae, Rosaceae, and Rutaceae families accounted for approximately 4.95 % of plant diversity at five species each. Next came the Amaranthaceae, Araceae, Compositae, Cucurbitaceae, and Rubiaceae families, which each made up around 3.96 % of the total species count at four species each. In comparison, the Malvaceae family occupied around 2.97 % of the total with three species.

The last grouping of note contained the Anacardiaceae Apocynaceae, Arecaceae, Begoniaceae, Myrtaceae, Nyctaginaceae, Piperaceae, and Zingiberaceae, families that each accounted for 1.98 % of the diversity count with two species. Each of the remaining 24 families occupied only around 0.99 % of the species diversity. Only seven out of 93 genera had more than one species (figure 21). The six most abundant species were coffee (*Coffea arabica* L.), starleaf begonia or xocoyol (*Begonia heracleifolia* Cham & Schltdl.), chiltepin pepper (*Capsicum annuum* var. *glabriusculm* (Dunal) Hieser & Pickersgill), banana (*Musa* sp.), garden ginger (*Renelmia alpinia* (Rottb.) Maas), and tomato (*Solanum lycopersicum* L.).

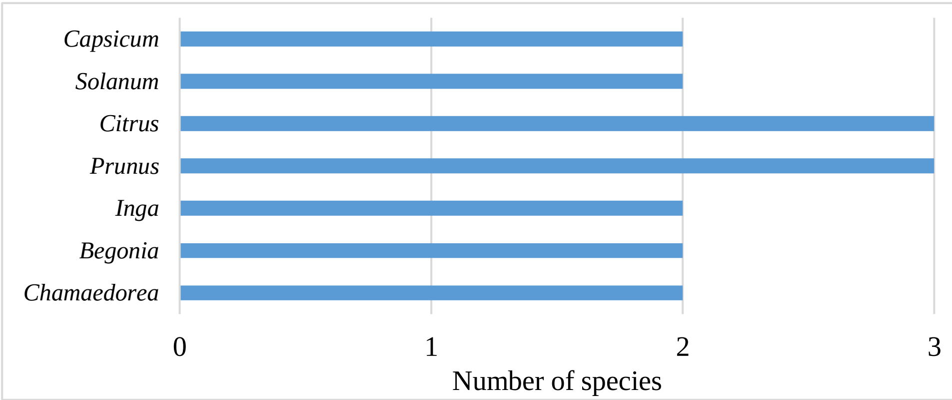

Figure 21. Genera with more than one species found in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico
Source: Elaborated by the authors

The six most frequent individual species documented in the homegardens were chiltepin pepper (*C. annuum* var. *glabriusculm*), papaya (*Carica papaya* L.), banana (*Musa* sp.), starleaf begonia (*B. heracleifolia*), Mexican tea (*Dysphania ambrosioides* (L.) Mosyakin & Clemants) and coffee (*C. arabica*). Other species such as coriander, orange, squash, the Mexican marigold flower, and corn also had a high rate of frequency and abundance. The medicinal plants most frequently found in the gardens were *Allium schoenoprasum* L., *Eryngium foetidum* L., *Xanthosoma sagitifolium* (L.) Schott., *D. ambrosioides*, and *Citrus sinensis* (L.) Osbeck.

Regarding intraspecific diversity, about ten species (table 9) in the study units had more than two varieties, i.e., a total of 20 varieties were found. The results obtained via participant observation indicate that these varieties within the same species mainly differed either in the color of the fruit, leaf size, taste, or in phenology. However, this study did not identify the varieties taxonomically, only by the local empirical knowledge. We did, however, break down the species by the degree of management: of the 101 plant species found in the study area, five were protected, 27 were fomented, and 69 were cultivated.

Table 9. Plant species with more than one variety found in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

N°	Scientific name	Family	Common name
1.	*Begonia heracleifolia* Cham & Schltdl.	Begoniaceae	Starleaf begonia
2.	*Capsicum annuum* var. *glabriusculm* (Dunal) Hieser & Pickersgill	Solanaceae	Chiltepin pepper
3.	*Carica papaya* L.	Caricaceae	Papaya
4.	*Coffea arabica* L.	Rubiaceae	Coffee
5.	*Musa* sp.	Musaceae	Banana
6.	*Xanthosoma sagittifolium* (L.) Schott	Araceae	Arrowleaf elephant's ear
7.	*Zea mays* L.	Poaceae	Corn
8.	*Renealmia alpinia* (Rottb.) Maas.	Zingiberaceae	Garden ginger
9.	*Bougainvillea glabra* Choisy	Nyctaginaceae	Bougainvillea
10.	*Prunus serotina* Ehrh	Rosaceae	Wild black cherry

Source: Elaborated by the authors

The results of the species richness, diversity, and dominance indices (table 10) indicated that the highest species diversity value of 49 was found in garden N°1 and the lowest value of 20 in garden N°11. Species richness and their functions are essential attributes to highlight the overall diversity of the homegardens, and according to the Margalef Index, homegardens with a high species richness value are more ecologically sustainable: in this case, garden N°1 had the highest value as well. The results of the Shannon-Wiener Index, which measures the proportional abundance of species within the homegarden, showed that garden N°11 had the minimum value at 2.863, and garden N°1 again had the maximum value at 3.697. According to the Pielou Index, all the gardens represented high equitability, i.e., close to 1.0.

Table 10. Plant species diversity found in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

Garden	**Species richness Index**			**Proportional abundance Index**			**Equity**
N°.	**Species richness (S)**	**Number of individual plants**	**Margalef Index**	**Shannon-Wiener Index**	**Simpson Dominance Index**	**Simpson Diversity Index**	**Pielou Index**
1.	49	118	10.06	3.697	0.02901	0.971	0.95
2.	42	96	8.983	3.489	0.03863	0.9614	0.9374
3.	38	84	8.35	3.423	0.03912	0.9609	0.9438
4.	47	198	8.699	3.254	0.08157	0.9184	0.8451
5.	46	121	9.3832	3.614	0.03258	0.9674	0.9438
6.	37	106	7.7196	3.389	0.03969	0.9603	0.9413
7.	23	47	5.7141	2.98	0.0593	0.9407	0.9503
8.	22	77	4.834	2.969	0.05616	0.9438	0.964
9.	28	78	6.1973	3.124	0.05095	0.949	0.9419
10.	39	124	7.88	3.464	0.0359	0.9641	0.9435
11.	20	39	5.19	2.863	0.06377	0.9362	0.9558
12.	32	93	6.84	3.293	0.04197	0.958	0.9502

Source: Elaborated by the authors

Species diversity of fauna (domesticated animals and edaphic macrofauna)

In terms of fauna species diversity, five species belonging to four families and five genera were found in the study units (table 11).

Table 11. Presence of domesticated animals found in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

Common name	Scientific name	Family	Homegarden Number	Total, gardens
Pigs	*Sus scorfa*	Suidae	1, 2, 4, 5, 7, 11	6
Chickens	*Gallus gallus*	Phasianidae	All study units	12
Turkeys	*Meleagris gallopavo*	Phasianidae	2, 3, 4, 7	4
Geese	*Anser anser*	Anatidae	3	1
Ducks	*Carina moschata*	Equidae	10	1

Source: Elaborated by the authors

The results (table 12) of the edaphic macrofauna evaluation in the study units indicated that homegardens N°5, 6, 12, 1, and 2 (in value order) reported the highest number of macrofauna, followed by gardens N°7, 9, and 3. Conversely, some gardens such as N°4, 10, and 11 reported a low number of individuals, either due to agrochemicals or lack of nutrients in the soil.

Table 12. Edaphic macrofauna diversity in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

	Number of individual/m² found in each homegarden											
Name of taxa	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Arthropoda	100	200	200	-	500	300	100	-	100	-	-	400
Spiders	200	100	-	-	200	200	-	-	200	-	100	-
Centipedes	-	100	-	-	100	100	100	-	-	-	100	-
Woodlice	-	100	-	-	100	100	-	-	200	-	-	-
Ants	100	200	100	100	100	200	400	-	100	100	100	100
Coleoptera	-	-	-	-	-	-	-	100	-	-	-	100
Cockroaches	-	-	-	-	-	-	-	100	-	-	-	100
Earthworm	-	100	300	-	200	100	-	200	-	100	-	400
Millipedes	600	200	-	-	1800	800	-	-	200	-	-	100
Total, individual/m²	**1000**	**1000**	**600**	**100**	**3000**	**1800**	**800**	**400**	**800**	**200**	**300**	**1200**

Source: Elaborated by the authors

Structural diversity of flora

The documented flora consisted predominantly of herbaceous species (44 species), followed by tree (27) and shrub species (19). The other 11 species belonged to another growth habit or life forms such as palm, climber, or succulent (appendix 1).

The vertical organization of homegardens

Regarding vertical structure, the classification system by Krishnamurthy and Ávila (1999) of herbaceous, shrub, and arboreal strata was used. In general, we found four layers or strata in the study area. These strata were distributed at different heights from zero to over five meters (table 13). The ground or lower layer (ranging from 0-1 m) consisted mainly of herbaceous plants as the dominating life forms or growth habits such as medicinal, vegetable, and ornamentals, including potted plants. The second lower-middle layer (1-3 m) consisted of shrub plants such as papaya (*C. papaya*) and coffee (*C. arabica*). The third upper-middle layer (3-5 m) was comprised of trees such as oranges (*C. sinensis*) and guava (*Psidium guajava* L.). In the top layer (above 5 m), trees like mango (*Mangifera indica* L.) and avocado (*Persea americana* Mill.) were found. For more detail on the vertical organization of all species found in the study area, see appendix 1.

Table 13. Vertical distribution of species in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

Strata	Number of species in each stratum
0-1 m	42
1-3 m	30
3-5 m	7
Above 5 m	22

Source: Elaborated by the authors

Horizontal organization of homegardens

The horizontal structure classification identifying ten management zones (fruit trees, shaded coffee, ornamentals with shade trees, multi-purpose trees, herbaceous crops, ornamentals with vine-crop shade, grass, other, and ornamentals with artificial shade) in tropical homegardens by Méndez (2000) was used to analyze the study units. We found that most of the Totonac homegardens were distributed into seven management zones (table 14).

Table 14. Management zones identified in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

N°.	**Management zones**	**Homegarden N°**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1.	Fruit trees	x	x	x	x	x	x	x	x	x	x	x	x
2.	Ornamental plants	x	x	x	x	x	x	x	x	x	x	x	x
3.	Herbaceous crops[a]	x	x	x	x	x	x	x	x	x	x	x	x
4.	Multi-purpose trees[b]	x	x	x	x	x	x	-	-	x	x	x	x
5.	Animal sheds	x	x	x	x	x	-	x	-	-	-	-	-
6.	Sheds for seed and fuelwood	x	x	x	x	x	x	x	-	-	-	x	x
7.	Residence area	x	x	x	x	x	x	x	x	x	x	x	x
Notes: a - food, medicine & spices; b - shade, forage, fuelwood, timber, and ornamentals													

Source: Elaborated by the authors

Functional diversity

Plant species found in the Totonac homegardens had multiple functions. More than 83 % of species were used for two or more purposes. Of the remaining 17 species, 16 were utilized by the owners solely for ornamental purposes and one for medicine. Based on the opinions of the head of each household, all the mentioned uses were classified within 13 categories (figure 22). The category use of sustenance here refers to the supporting services such as refuge, recreation, shade, habitat for wild animals, supporting material as a tutor, etcetera.

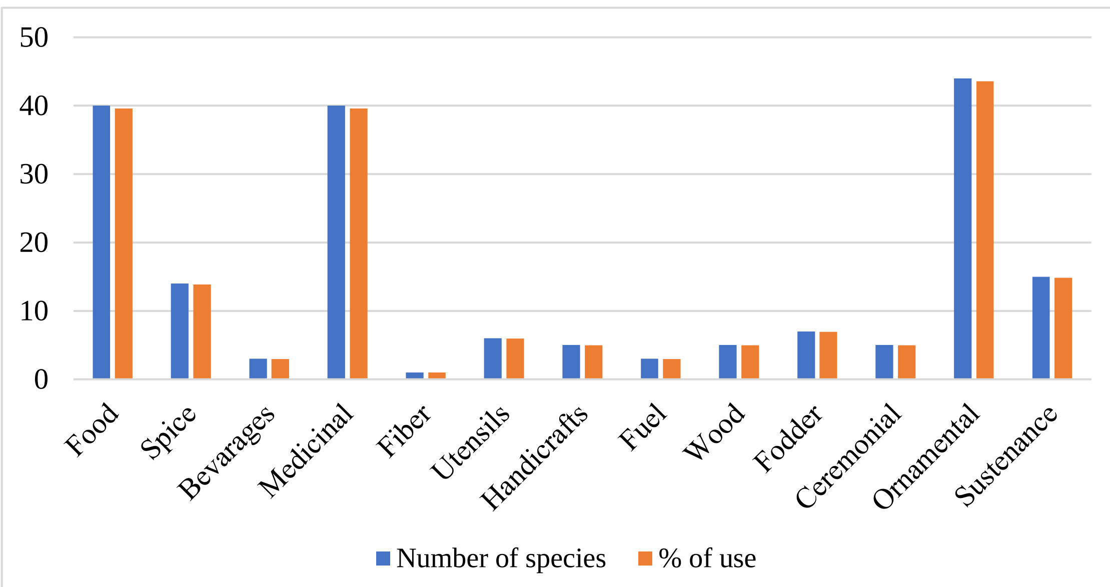

Figure 22. Principal use categories of plant species in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico
Source: Elaborated by the authors

Most species found in the study area belonged to the category of ornamental use (43.56 %), followed by food (39.6 %), medicine (39.6 %), sustenance (14.85 %), spice (13.86 %), fodder (7.92 %), utensils (5.94 %), beverages (5.94 %), handicrafts (4.95 %), ceremonial (4.95 %), wood (3.96 %), fuel (2.97 %), and fiber (0.99 %). Similarly, the parts of the plant most frequently associated with use (table 15) were leaves (49.5 %), the whole plant or tree (44.55 %), fruit (31.68 %), flowers (19.8 %), and seeds (8.91 %).

Table 15. Plant structure used in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico

N°.	Plant Structure Used	Species	% of use
1.	Leaves (L)	50	49.50 %
2.	The whole plant (P)	45	44.55 %
3.	Fruit (Fr)	32	31.68 %
4.	Flower (F)	20	19.80 %
5.	Seed (Se)	9	8.91 %
6.	Stem (S)	5	4.95 %
7.	Bulb (B)	3	2.97 %
8.	Trunk (Tr)	3	2.97 %
9.	Grain (G)	2	1.98 %
10.	Latex (La)	2	1.98%
11.	Tree bark (Tb)	1	0.99%
12.	Branches (Br)	1	0.99%
13.	Sheath (Sh)	1	0.99%
14.	Stalk or cane (St)	1	0.99%

Source: Elaborated by the authors

Discussion

Totonac homegardens and flora diversity

The current research confirmed that the studied Totonac homegardens possess a high level of agrobiodiversity: they contained a total of 101 plant species belonging to 45 families, and 93 genera, four vegetation strata organized vertically, ranging from four to seven zones of management arranged horizontally, and about 13 categories of use or functions.

It is important to note that the number of plant species (101) found in the sample of 12 homegardens in the study area differed from previous studies of homegardens in other communities or regions of Mexico. See, for instance, the 223 species reported by Del Ángel-Pérez and Mendoza (2004) in the backyards of the Totonac community of Coxquihui, State of Veracruz; 150 species reported by De Clerck and Negreros-Castillo (2000) in the homegardens of five Mayan communities in the State of Quintana Roo; 233 species reported by Blanckaert, Swennen, Flores, Rosas-López and Lira (2004) in the homegardens in the San Rafael Coxcatlán community, in the Valley of Tehuacán-Cuicatlán in the State of Mexico; 233 species reported by Aguilar-Støen, Moe and Camargo-Ricalde (2009) in the municipality of Candelaria Loxicha, State of Oaxaca; and 280 by Avilez-López, Van der Wal, Aldasor-Maya and Rodríguez-Robles (2020), in the municipality of Comalcalco, State of Tabasco.

Aguilar-Støen et al. (2009) reported that plant species belonging to families such as Myrtaceae, Fabaceae, Araceae, and Solanaceae dominate the homegardens of Oaxaca. These findings align with the results of this paper, where more than 76.23 % of the species registered in the study area belonged to the 21 families, namely Amaranthaceae, Anacardiaceae, Apocynaceae, Araceae, Arecaceae, Begoniaceae, Compositae, Cucurbitaceae, Euphorbiaceae, Fabaceae, Lamiaceae, Malvaceae, Myrtaceae, Nyctaginaceae, Piperaceae, Poaceae, Rosaceae, Rubiaceae, Rutaceae, Solanaceae, and Zingiberaceae. However, the remaining 23.76 % of the species that belonged to the other 24 families were intentionally cultivated and managed to meet the daily needs of household members. For example, species such as avocado (Lauraceae), banana (Musaceae), black sapote (Ebenaceae), cedar (Meliaceae), coriander (Apiaceae), papaya (Caricaceae), turpentine or gum tree (Burseraceae), vanilla (Orchidaceae), and ornamental plants (Liliaceae, Heliconiaceae, Iridaceae) were prevalent in the study units.

Also, most of the food, medicinal, and ornamental plants found in the Totonac homegardens were almost exclusively planted by the women of each household based on their individual and cultural preferences. For instance, tomato and chile were the most preferred plants, as indispensable ingredients in the local traditional diet.

Only about 40 % of the species found in the study units were native to the region, and the rest were introduced. This is opposite to the results found by other authors (Larios, Casas, Vallejo, Moreno-Calles, & Blancas, 2013; Toledo, Ortiz-Espejel, Cortés, Moguel, & Ordoñez, 2003) who reported a high number of native species in homegardens of Mexico, illustrating their high relevance for regional conservation of agrobiodiversity and ongoing species domestication.

Despite these differences with other studied regions, the current study results indicated that the variety and variability of plant species in the study zone reflected the conservation of traditional knowledge relevant to the management and use of both native and introduced species to satisfy the subsistence needs of the local people. Moreover, although plant species richness, abundance, and dominance between study units were significantly different, all study units still possessed high diversity levels according to the results of the diversity indices. The current study did not directly evaluate the reasons for the differences between study units; however, they may be due to changing economic and socio-cultural aspects in the study zone, such as rural migration, the limited ability of the elderly to manage homegardens, and a lack of appreciation among youth for homegardens.

Totonac homegardens and diversity of fauna

Regarding the diversity of fauna species, the current study only considered domesticated animals and edaphic macrofauna. The most common domesticated animals found in the study units were chickens, hens, pigs, turkeys, and ducks. Most of the study units raised animals in enclosed spaces or sheds within the garden. Very few units had free-roaming chickens in the garden. Although garden owners expressed that they were interested in raising all four of these domesticated animals, chickens and hens were preferred by most. This was mainly due to the lower demand for labor and care for these animals and their short reproduction time. Chicken is also one of the most readily available foods, as it can be sold or consumed rapidly. Animals such as geese, ducks, and turkeys were less common compared to chickens or pigs and raised in small numbers. Although animals such as donkeys (*Equus asinus*) and horses (*Equus caballus*) are used for labor and transportation purposes in the community, they were not raised in the studied units. But other farmers in the community protected these animals in a bit of space inside the homegardens. It is also essential to consider that these animal species are herbivorous. Their waste serves as fertilizer that the farmers apply to the plants of most significant interest within the orchards without spending money on it.

Raising animals in homegardens provided a continuous production of meat and eggs to meet the dietary protein needs of family members. One of the common characteristics found in the study area is that many families fed their animals by supplementing their diets with cereal, food scraps, and household waste. This indeed helps to minimize the cost of raising these animals. Taking care of animals in the homegardens also generated a permanent source of work, especially for women and children. The characteristics mentioned earlier regarding the choice, management, and use of domesticated animals found in the current study were similar to previous studies on traditional land-use practices of homegardens in many parts of Mexico (Mariaca, 2012) and the world (Kumar & Nair, 2006).

When evaluating the diversity of fauna, it is recommended to consider all levels of agrobiodiversity associated with the study site such as birds, insects, and microorganisms, including micro, meso, and macrofauna. All these organisms are fundamental for the maintenance of the structure and functions of homegardens. Given the absence of information on Totonac homegardens, the current study took the first step in this direction by evaluating the edaphic macrofauna in all the study units. The high value of edaphic macrofauna recorded in some gardens depended mainly on the type of energy employed in the management of land, i.e., with limited use of agrochemicals as well as the incorporation of animal manure or food waste in the soil.

Totonac homegardens and structural diversity

The results indicated that the spatial organization of the study units was diverse both horizontally and vertically. Specifically, the vertical structure of the homegardens in the study area had four layers (herbs ranging from 0-1 m; shrubs from 1-3 m; medium-sized trees from 3-5 m and trees of >5 m with high ramification) with different life forms or growth habit. This result coincides with other authors (Caballero, 1992; Fernandes & Nair, 1986; Krishnamurthy, Krishnamurthy, Rajagopal, & Peralta, 2017; Lope-Alzina & Howard, 2012) who found that most of the homegardens are distributed vertically with at least three layers: lower levels contained herbs and food or medicinal plants (0-2 m), intermediate levels have shrubs or bushes and young, low trees (3-5 m), and upper levels contained tall trees (5-10 m). However, our findings differ from the study by De Clerck and Negreros-Castillo (2000), who identified six layers or strata in Mayan-Yucatecan homegardens in the state of Quintana Roo in Mexico.

Herbaceous species dominated the study units compared to other life forms or growth habits, which coincides with the findings of other homegarden studies where the frequency of herbaceous species is higher than tree or shrub species (Krishnamurthy & Ávila, 1999; Krishnamurthy et al., 2017). Also, the ornamental and herbaceous crops were planted very near to residences.

In terms of the horizontal distribution of management zones, the seven zones (Fruit trees, ornamental plants, herbaceous crops (such as food, medicine, and spices), multi-purpose trees (such as shade, forage, fuelwood, timber, and ornamentals), animal sheds, sheds for seed and fuelwood, residence area) found in Totonac homegardens resembled with other studies (Chablé-Pascual, Palma-López, Vázquez-Navarrete, Mariaca-Méndez, & Ascensio-Rivera, 2015; Mariaca, 2012) that identified mixed zones of fruit trees, ornamental plants, herbaceous crops, shade trees, residence area, animals sheds. Also, other studies mentioned the irregular arrangements of management zones without any specific design like Totonac homegardens. Interestingly, most of the current study units were delimited using either fence or plant species.

Interestingly, homegardens in the study area were generally found in the house's backyard and delimited using either fence or plant species. Also, most of the homes in the study area were made of concrete and divided into different sections that include rooms, kitchens, and restrooms. Other types of structures such as barns or sheds in the study units are used generally to store food harvest, firewood, or other materials and sometimes as stables for livestock.

Totonac homegardens and functional diversity

Many products obtained from the homegardens in the study area were used for self-consumption by the family members, mainly to ensure food security. Occasionally, excess products were either sold or exchanged in the community. But the income from the homegarden products was irregular and varied between seasons and gardens. Reported plant species in the use categories of food, spices, and beverages were utilized daily and occupied a significant role in the Totonac culinary culture. Members of the family generally used medicinal plants to treat stomach pain, headaches, body pain, injuries, wasp stings, skin infections, diarrhea, the common flu, and skin parasites.

Many species were consumed as infusions or tea, and others were applied externally (the current study did not consider the infusion of certain species as beverages but instead as medicine). The use of these medicinal plants by locals was mainly driven by the traditional knowledge accumulated and transmitted from generation to generation. Fuel, fiber, forage, and wood species in the homegardens were planted in minimal quantities, as they were easily available in the nearby natural vegetation areas or forests.

The conservation of ceremonial species such as *Ocimum basilicum* L. and *Sambucus nigra* L., had ritual uses for the family. Other species such as *Tagetes erecta* L., *Euphorbia pulcherrima* Willd. Ex Klotzsch., *Gomphrena globosa* L. were used for decoration in religious and cultural festivals. However, many members of the study units did not mention or freely speak about any ritual or magic purposes of plant species. This is probably either due to a low trust level with the researchers and fear of being judged for their cultural beliefs. Thus, the current study mentions very few species in the ceremonial use category, though participants did not initially identify more plant species in this category.

The use of utensils mainly included species that provided leaves to cover traditional food, such as tamales, etc. Species such as palm or pacaya (*Chamaedorea tepejilote* Liebm. Ex Mart) and the jícara or gourd tree (*Crescentia cujete* L.) were used to elaborate handicrafts such as necklaces and earrings. The fiber of Jonote (*Heliocarpus appendiculatus* Turcz) was used to craft hanging baskets called “Huacal” that were made by carving tree bark or wood into circular shapes and knotting Jonote fibers by hand. Indigenous people in the study area have commonly used these rustic baskets since pre-Hispanic times - a tradition that continued to the present day and often used to carry babies while doing chores or to collect harvested products from the field, such as corn.

The ornamental species were mainly chosen based on the preferences of the women in each household and for their aesthetic value. Many fodder species were used to provide food for domesticated animals, along with food waste from the house. The species under the sustenance use category generally served as a refuge to wild animals by providing either food or habitat. Also, these species were used to support many climbing plants and provide shade, etc.

When analyzing the functions of domesticated animals, pigs, chickens, turkeys, and geese were mainly used to meet the egg, animal oil, and meat consumption needs of family members. In other words, they were the principal source of protein, B complex vitamins, and minerals such as iron and calcium, and phosphorus in the family diet. In addition, their manure also constituted a valuable fertilizer that helped to increase the quality of homegarden soil. Moreover, animals were raised and slaughtered to prepare traditional foods during religious festivals, a common feature of Totonac culture where this traditional food is shared by members of the whole community.

Totonac homegardens and management

Totonac homegardens resembled the management characteristics observed in many other studies, particularly within Mexico (Del Ángel-Pérez & Mendoza, 2004, Mariaca, 2012). Many plants belonging to the cultivated plant category that is produced to meet specific needs. Some wild (not domesticated) plants were either protected or fomented by the owners of the study units. Family labor was utilized to manage activities such as weeding, pruning, harvesting, etc. Manual energy or limited use of fossil energy was a common characteristic of traditional homegardens. Also, the owners of the Totonac homegardens generally considered the homegarden as one of the sub-systems of the umbrella agroecosystem of *milpa* or coffee production units.

Conclusions

The studied Totonac homegardens were represented by 101 plant species belonging to 45 families and 93 genera, four vegetation strata organized vertically, four to seven zones of management organized horizontally, and about 13 categories of management use or functions. The identified richness and diversity of plant and animal resources in the studied units not only provided food security but also fulfilled multiple ecological, economic, and socio-cultural functions, which were highly linked with the cultural preferences of family or household members. In summary, Totonac homegardens in the study area with high diversity levels of species, structure, and functions significantly contributed to safeguarding agrobiodiversity as well as their associated cultural identity.

However, the current environmental, economic, and socio-cultural challenges in the study zone are threatening the very existence of this traditional land-use practice. Thus, there is an urgent need to promote homegardens through the design of efficient local government policies, both as a repository of biocultural heritage through with indigenous knowledge is transmitted, as well as a source to enhance the livelihood of native people. This could be a viable win-win strategy towards achieving bottom-up development in the rural landscapes of Mexico.

Thus, the current study recommends focusing on the following points in future research on homegarden agrobiodiversity: i) conducting a comparative analysis of the biodiversity (including intraspecific and associated diversity) level at different spatial and temporal scales to determine the exact status of agrobiodiversity in the study zone; ii) designing a unique mathematical model or program to measure the total *taxa* involved in the complex agroecosystems such as homegarden; iii) assessing the multiple ecological, economic, and sociocultural functions of the homegardens using a holistic approach to realize an in-depth analysis of the functional diversity of these systems.

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5. EVALUATION OF THE SUSTAINABILITY BASED ON INTEGRAL RESILIENCE OF HOMEGARDENS IN TOTONACAPAN, MEXICO*

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Abstract

The rationality of management, use, and conservation of agrodiversity associated with traditional agroecosystems such as homegardens (HGs) changes due to the adverse modifications in the current ecological, economic, and sociocultural conditions derived from various natural and anthropogenic alterations. Consequently, putting at risk the resilience and sustainability of these systems in some rural communities of Mexico. This study aimed to evaluate the current degree of integral (ecological, economic, and cultural) resilience of homegardens as a basis to determine their degree of sustainability. Data were collected from thirty members of different generations, from 12 Totonac homegardens in Santiago Ecatlan, Puebla, during June 2018-July 2019. A conceptual framework of resilience was developed based on the hypothesis that the higher the magnitude of agrodiversity, the lesser the vulnerability and higher the resilience of HGs. A methodology with seven steps was adapted to operationalize this framework. Four components, 15 indicators were developed. The resilience score index (RI) was elaborated using both qualitative and quantitative methods. A multi-criteria analysis of FlowSort was performed to evaluate the sustainability of HGs based on their resilience category. The results of the RI showed that orchards H1, H4, and H5 did not exceed H2, while H10 registered the lowest RI, without differentiating from H8 and H9. The FlowSort analysis showed that H1, H2, H4, and H5 orchards belong to the category of high resilience, while the rest belong to medium resilience. Finally, orchards that belong to the category of high resilience were potentially sustainable than gardens of medium resilience. To conclude, HGs with high agrobiodiversity, management and conservation capacity, monetary gains, and organizational capacity contribute to increasing the integral resilience in the face of adverse challenges. Thus, the more significant the transmission, conservation, and improvement of agrodiversity associated with homegardens and the degree of appreciation for it by current and future generations, the greater the integral resilience and sustainability of homegardens Totonacapan.

Keywords: agrodiversity, biocultural heritage, inclusive development, multifunctional agriculture, vulnerable agroecosystems.

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Evaluación de la sostenibilidad a base de resiliencia integral de huertos familiares en el Totonacapan, México

Resumen

La racionalidad del manejo, uso y conservación de la agrodiversidad asociada a los agroecosistemas tradicionales como los huertos familiares (HFs) está cambiando debido a las modificaciones adversas en las condiciones ecológicas, económicas y socioculturales actuales derivadas de diversas alteraciones naturales y antropogénicas. Este estudio tuvo como objetivo evaluar el grado actual de resiliencia integral (ecológica, económica y cultural) de los huertos familiares como base para determinar su grado de sostenibilidad. Se recolectaron datos de treinta miembros de diferentes generaciones de 12 huertos familiares totonacas en Santiago Ecatlán, Puebla durante junio 2018-julio 2019. Se desarrolló un marco conceptual de resiliencia basado en la hipótesis de que cuanto mayor es la magnitud de la agrodiversidad, menor vulnerabilidad y mayor resiliencia integral de los HF. Se adaptó una metodología con siete pasos para operacionalizar este marco. Se desarrollaron cuatro componentes, 15 indicadores y 32 variables. El índice de puntaje de resiliencia (IR) se elaboró utilizando métodos tanto cualitativos como cuantitativos. Se realizó un análisis multicriterio de FlowSort para evaluar la sostenibilidad de los HG en función de su categoría de resiliencia. Los resultados del IR mostraron que los huertos H1, H4 y H5, no superaron el H2, mientras que H10 registró el IR más bajo, sin diferenciarse de H8 y H9. El análisis de FlowSort mostró que los huertos H1, H2, H4 y H5 pertenecen a la categoría de alta resiliencia, mientras que el resto pertenece a la media resiliencia. Finalmente, los huertos que pertenecen a la categoría de alta resiliencia son más potencialmente sostenibles que los huertos de resiliencia media. Para concluir, los HFs con alta agrobiodiversidad, capacidad de gestión y conservación, ganancias monetarias y capacidad organizativa, contribuyen a aumentar la resiliencia integral ante desafíos adversos. Así, cuanto más significativa sea la transmisión, conservación y mejoramiento de la agrodiversidad asociada a los huertos familiares y el grado de aprecio de la misma por parte de las generaciones actuales y futuras, mayor será la resiliencia integral y la sostenibilidad de los huertos familiares del Totonacapan.

Palabras clave: Agrodiversidad, patrimonio biocultural, desarrollo incluyente, agricultura multifuncional, agroecosistemas vulnerables.

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1. Introduction

Globally, homegardens (HGs) have been identified as one of the oldest practices next only to shifting (swidden, slash and burn, or nomadic) cultivation dating back to more than 10,000 years ago. And many scholars classify HGs as one of the essential but complex agroforestry production systems that comprise “intimate, multistory combinations of various trees and crops, sometimes in association with domestic animals around the homestead” (Kumar and Nair, 2006).

Due to the absence of the standard definition, for this paper, in general, HGs are described as a system that encompasses the production of a diverse array of the plant (such as vegetables, fruits, food crops, spices, herbs, ornamental and medicinal) and animal (both domestic and wild) species that mimics not only the natural ecosystem but also fulfill diverse environmental, economic, and sociocultural functions in the portion of the land near the family household (Torquebiau, 1992; Hoogerbrugge and Fresco 1993).

HGs have been highlighted considerably as one of the predominant subsistence agricultural land-use units among small-scale farmers from different cultural and ethnic groups, particularly in the tropics of Mesoamerica (Kumar and Nair, 2004; Lok, 1998; Galhena, Freed, Maredia, 2013; Ordoñez Diaz, Benjamin Ordoñez, and Lope-Alzina, 2018; Rajagopal *et al*., 2021). For example, in Mexico, archaeological and ethnohistorical evidence from ancient cultural areas suggests that HGs played a significant role in the development of many pre-colonial societies such as the Mayans, Aztecs, and Totonacs by assuring annual food production and permanent settlements (Caballero, 1992; Del Angel-Pérez and Mendoza, 2004).

Even now, HGs represent a valuable integral component of family farming or local indigenous food production systems such as milpa (corn-fields), potreros (cattle-raising areas), agricultural fields other than milpa, and widely practiced by many indigenous populations, especially in the rural landscapes of Mexico (Toledo, Ortiz-Espejel, Cortés, Moguel, and Ordoñez, 2003; Mariaca, 2012).

According to SAGARPA-FAO (2013), out of the total existing 5.3 million rural economic units in Mexico, 3.9 million (73%) are considered subsistence farming units. And HGs were not only considered as part of these units, but it acts as an essential supplemental source of food and income for many smallholder farming families that fulfill their nutritional as well as economic security often daily, but mainly during periods of stress, e.g., harvest failure, unemployment, conflicts, disease or health disabilities (Lok, 1998; Mariaca, 2012).

Data evidence from several studies carried out until now emphasize that HGs can be an alternative sustainable development strategy in rural areas to improve agrobiodiversity conservation, food, and nutritional security, economic security, social cohesion, biocultural knowledge, ecosystem processes, and services, only if they are well adapted agronomically to the local environmental and agronomic (resources) as well as sociocultural (traditions and cultural preferences) conditions (Krishnamurthy, Krishnamurthy, Rajagopal, and Peralta, 2017; Rajagopal *et al*., 2021).

However, despite the global recognition of HGs potential to contribute to sustainable rural development, on the one hand, the discontinuity of these traditional land-use practices due to the current economic and socio-cultural challenges (such as lack of family labor due to death, illness, or migration, loss of biocultural knowledge) threatening the provisioning of a supplemental source of food and income as well as ecosystem services for many smallholder farming families living in the rural landscapes of Mexico. Thereby significantly affects the sustainable livelihoods of the local people. On the other hand, the resilience (i.e., the capacity of the system to withstand, adapt, and transform changes) of these traditional agroecosystems itself threatened due to the current human-induced adverse global challenges (such as climate change, loss of biodiversity, cultural erosion) and consequently affected its overall sustainability.

Besides, notable studies carried out so far on homegardens are descriptive and have principally focused on its species composition, structural complexity, functional diversity (Gbedomon *et al*., 2015; Lope-Alzina and Howard, 2012;

Vibhuti, Bargali, and Bargali, 2018), biodiversity, food security and nutrient management (Montagnini, 2006; Cahuich-Campos, 2012; Agbogidi and Adolor, 2013) economic gains (Mohan *et al*., 2006), and sustainability issues (Torquebiau, 1992; Torquebiau and Penot, 2006; Chakravarthy, Puri, Subba, Pala, and Shukla, 2018). Yet, globally, studies on the agricultural sustainability of HGs based on their resilience (i.e., the ability to cope up with current global trends) is not evident or explored sufficiently, particularly in the State of Puebla, Mexico, among the cultural group of Totonac people (Rajagopal *et al.*, 2021).

Based on the above lines of thought, the present study aimed to evaluate the sustainability of homegardens based on its degree of integral (ecological, economic, and sociocultural) resilience in the Santiago Ecatlan community in the State of Puebla, Mexico. Also, this research explored the hypothesis that agrodiversity associated with homegardens and the degree of appreciation of it are the main aspects that determine the degree of resilience and sustainability of the local homegardens.

In other words, the higher the magnitude of agrodiversity, the lesser the vulnerability and the higher the integral resilience of HGs. And, the following sections present the conceptual framework to assess the resilience of HGs, the study site, a methodological framework to operationalize the proposed framework, results obtained, followed by discussion and conclusions.

2. The conceptual framework for resilience assessment of HGs

The resilience theory of socioecological systems (SES) is a valuable framework to understand the dynamic relationship between humans and the environment. It is an efficient model to analyze the capacity of a system to manage change or disturbances. Resilience in SES is measured in three ways: 1) the amount of change the system can undergo and still retain the same controls on function and structure; 2) the degree to which the system is capable of self-organization, and 3) the ability to build and increase the capacity for learning and adaptation

(Holling, 2001; Gunderson and Holling, 2002; Folke *et al.*, 2010; Cabell and Oelofse, 2012).

Agroecosystems such as homegardens represent the sub-system of SES with interactions between gardens and owner's families. According to Darnhofer, Bellon, Dedieu, and Milestad (2010), agroecosystems are too complex and variable in time and space for resilient models that answering the question "resilience of what to what" suggested by Carpenter, Walker, Anderies, and Abel (2001), and "the value of resilience thinking is more likely to be realized by identifying more general 'rules of thumb' for use by farmers and facilitators to guide farms, the industry sector, the national agricultural system and the interconnected parts of the international food and fiber system towards a more resilient orientation."

As resilience is an emergent property of systems that can be very context-dependent, particularly in spatial-temporal scales and perspectives (Carpenter *et al.*, 2001), many authors (Bennett, Cumming, and Peterson, 2005; Carpenter, Bennett, and Peterson, 2006; Darnhofer *et al.*, 2010; Cabell and Oelofse, 2012) suggest and affirm that developing sets of context-dependent surrogates or indicators is a more helpful approach to measure SES (including agroecosystems) resilience instead of resilience itself. This suggestion is mainly due to the inherent challenges involved in measuring the abstract and multi-dimensional nature of the resilience concept.

Cabell and Oelofse (2012) agree with Darnhofer *et al.* (2010) that precise resilience measurement in agroecosystems is complex. Therefore, it is helpful to develop resilience rules of thumb that are applicable across scales of time and space. Also, they suggest using an index of behavior-based indicators to identify the state of resilience in an agroecosystem (developed based on the characteristics of resilient SES in different contexts identified in other research studies). However, the attributes of agroecosystems depend on their structure and function, which in turn are influenced by various ecological, economic, and socio-cultural aspects. As homegarden agroecosystems are complex SES, they require a systemic approach that holistically assesses resilience.

According to Prior and Hagmann (2012), measuring resilience in a systemic approach would require three actions: a) articulating the system's essential components; b) methodology development; and c) aggregation of measured data. The resilience approach, indeed, integrates ecological, economic, and social aspects. Also, building resilience helps to reduce the system's sensitivity to shocks or changes or uncertainty and is done mainly based on endowments (e.g., livelihood assets) and diversity of crops, wild flora, and fauna (Adger, 2000; Milestad and Darnhofer, 2003; Speranza, 2010; Jacobi *et al.*, 2013).

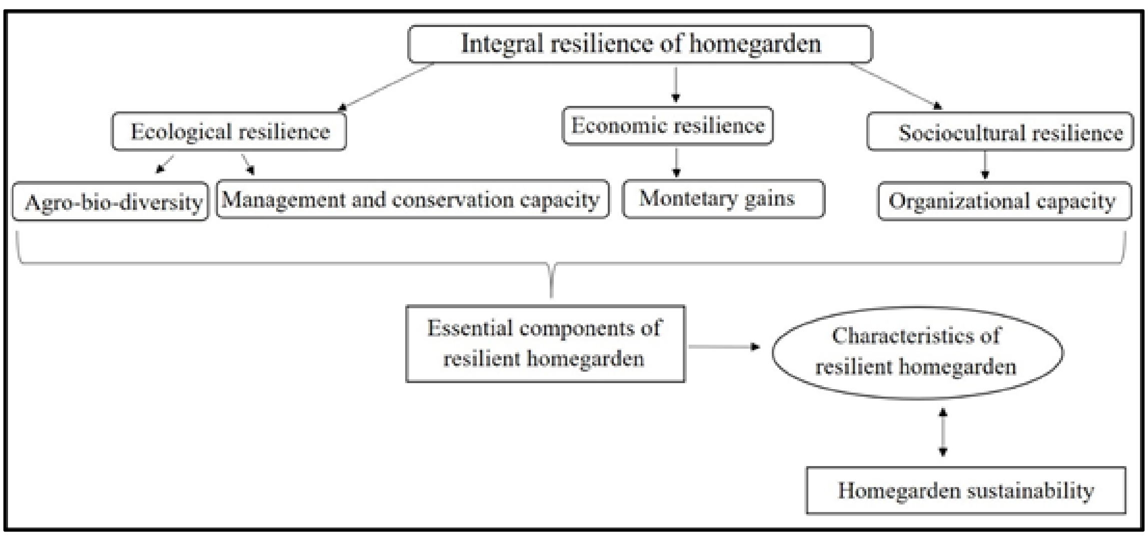

Figure 23. The conceptual model for assessment of homegarden resilience.

(Source: Elaborated by the authors).

According to Córdoba, Triviño, and Calderón (2020), complex systems such as agroecosystems are subject to constant change and fluctuation, measuring resilience to specific events that cause shock or stress is not always possible, but identifying their degree of resilience at any time is possible.

Therefore, it is fundamental to identify the elements of agroecosystems that either support or inhibit resilience using a complementary conceptual and methodological framework. Thus, it is crucial to identify alternative scenarios and new directions desired by the farmers when confronted with changes or shocks and achieve structural transformation through public policies or management plans.

Although there are diverse methodological frameworks to measure resilience, measuring the degree of integral resilience in agroecosystems (such as homegarden) using a holistic approach in the rural contexts is still lacking. Therefore, the current study developed a conceptual model for the operationalization of resilience measurement of the homegarden agroecosystem (Figure 23).

This model included or adopted the following four main components (considered proxies for the resilience of HG agroecosystem) that are fundamental to maintain homegardens structure and function, which influence the system's resilient characteristics and sustainability. They are: 1) agrobiodiversity (ABD), 2) management and conservation capacity (MCC), 3) monetary gains (MG), and 4) organizational capacity (OC).

The adoption of the above components indeed based on the consideration that the magnitude of agrodiversity (i.e., management, agro-bio, and organizational diversity) influence significantly the ecological, economic, and socio-cultural resilience (i.e., desired outcome or behavior or characteristics) of the modified environment such as homegardens (Brookfield, 1999).

Also, a methodology framework was developed (adapted from Córdoba *et al*., 2020) to operationalize the conceptual model to analyze the current degree of the integral (economic, ecological, and sociocultural) resilience of twelve homegarden agroecosystems in an indigenous community in the State of Puebla, Mexico.

3. Materials and Methods

3.1. Study area

The current study was conducted in the community of Santiago Ecatlan, belonging to the municipality of Jonotla, in the State of Puebla, Mexico (Figure 24). It is located between the parallels 20°00′ and 20°10′ North latitude; meridians 97°27′ and 97°36′ West longitude; with an elevation between 550-680 m. a. s. l. The average annual temperature is 26°C, and the mean annual precipitation is 4100 mm.

According to García (2004), the symbols for this climate are A(C) (w) i' g (i.e., a warm climate that tends to be temperate, with a rainy season in summer, little temperature oscillation, and an annual march of the Ganges type temperature). Leptosol (48%), Regosol (37%), Phaeozem (8%), and Andosol (4%) are the predominant soil type in the study area (National Institute of Statistics and Geography [INEGI], 2009). It is covered with mountain mesophilic and high evergreen forest types of vegetation. Due to the presence of high biological diversity, the study area comes under the priority land regions (RTP-105) of the National Commission for the Knowledge and Use of Biodiversity, i.e., CONABIO (Arriaga *et al*., 2000).

Regarding sociocultural characteristics, the community has access to education and sports through a pre-primary school in the town, El Colegio "*Angelica Castro de la Fuente*," and a primary school, El Colegio "*Antropólogo Julio de la Fuente*," as well as a football and a basketball court. The total population in the community is around 710, of which 334 are men and 376 are women. Of this total population, approximately 61% (433) belong to the age group of 15-59 years, 17.7% (126) belong to above 60 years, and 21.3% (151) within 14 years age group category. And 100.00% of the population is indigenous (Totonac), and 84.37% of the inhabitants speak an indigenous language. About 4.51% of the people that speak an indigenous language do not speak Spanish. Of the total population, 21.1% (10.18% of men and 22.34% of women) are illiterate.

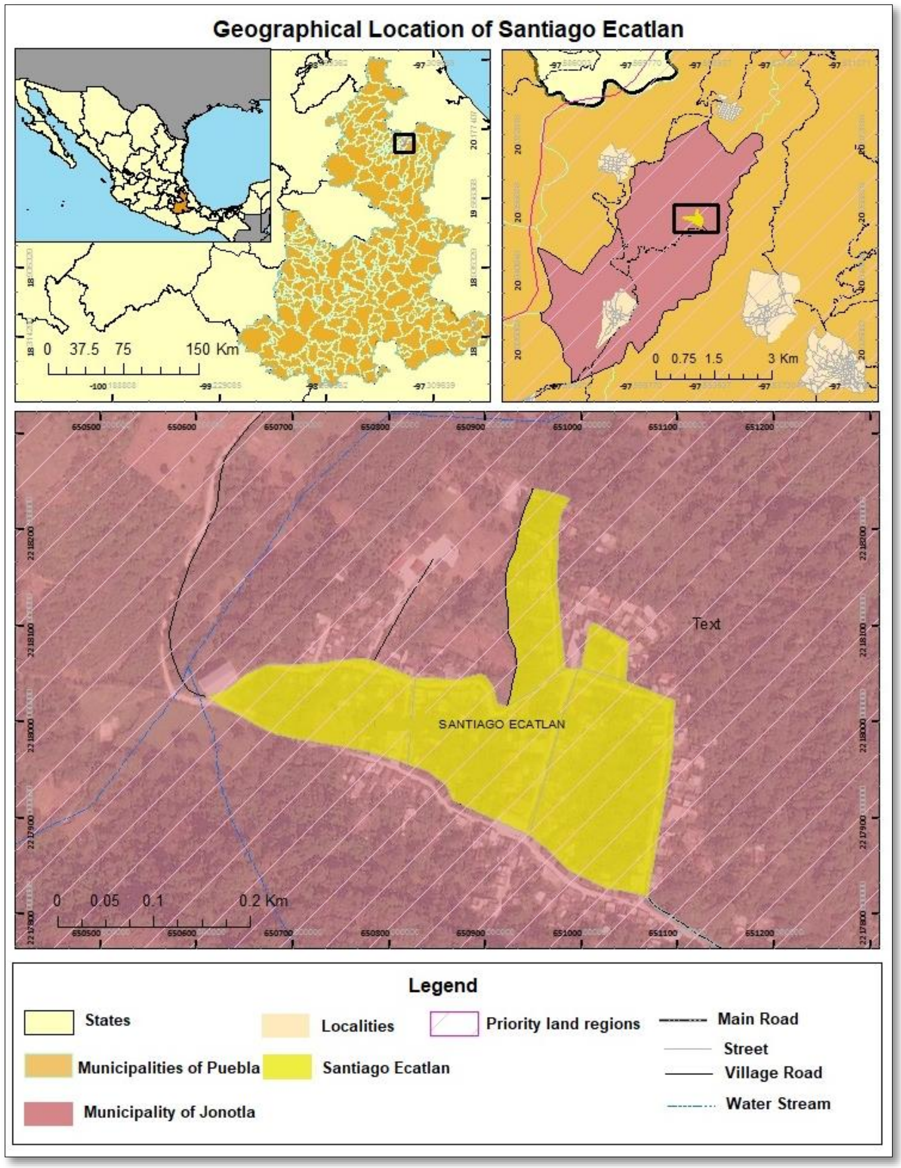

Figure 24. Map of the study area showing the location of Jonotla Municipality in the State of Puebla, Mexico.
(Source: Elaborated in ArcGis 10.3 version)

The area is highly marginalized, and the average homestead area is 300-500 meters and approximately 214 households. It is a rural town with access to potable water, electricity, telephone but lacks drainage (a septic tank is used). Its streets are paved, and the community has a two-lane highway that communicates with the municipality of Jonotla. However, the road is not in good condition due to rain, etc.

Also, the study area has natural resources such as limestone deposits and forests that are exploited as lumber for construction. The primary sector is mainly made up of agriculture (60%), grassland (25%), forest (6%), and jungle (6%). The use of the land is mainly for agriculture and housing. Agriculture is the main occupation, and slash burn agriculture is the predominant traditional land-use activity practiced in natural or forest-type vegetation patches. And seasonal beans, calabash chiltepin, coffee, corn, maize, groundnut, and vanilla production dominates in the area (INEGI, 2009).

3.2. Sampling

A sample of 12 homegardens was selected based on the criteria of availability and willingness to participate in the research process using the snowball method of the non-random sampling technique. Also, 30 members (16 women, nine men aged between 21 to 90 years, and five children aged between 6 to 17 years) from the selected study units participated in the research. Although the members who participated represent just 5% of the total population in the study area, it is vital to notice that they represent three generations (father, son, grandson). Therefore, the collected data in this research corresponds to a period of at least 30 – 60 years of experience or memory of the elders in the study units.

3.3. The methodological framework for resilience assessment of HGs

The methodological framework proposed in the study to evaluate the integral resilience of homegardens was modified from Córdoba *et al*. (2020) and consisted of the following phases:

1) Selected indicators and variables for assessing each component of the homegarden agroecosystem based on the conceptual model designed.

The four main ecological, economic, and sociocultural components (i.e., agrobiodiversity, management and conservation capacity, monetary gains, and organizational capacity) of homegardens per se are difficult to measure.

Therefore, this study proposed a set of indicators and variables for each component of homegardens fundamental to building its resilience.

Table 16. Performance criteria matrix of ecological resilience variables.

Component	**V***	**Range of values to resilience (R)**				**Criteria**
		High R	**Medium R**	**Low R**	**None**	
Agrobiodiversity	f1**	80	40	20	0	Number of species
	f2	10	5	2	0	Number of species
	f20	6	4	2	0	Vertical organization
	f21	6	4	2	0	Horizontal organization
	f3	9	7	3	0	9 zones
	f4	15	10	5	0	Total categories found 13
	f22	12	8	4	0	months/year
Management and conservation capacity	f5	900	400	200	0	Tropical zone-450 individuals/m^2
	f23	365	240	180	0	days/year
	f24	0	100	500	1000	meter
	f25	0	5	10	20	Number of plants
	f26	0	25	50	100	Percentage of animals
	f6	7	4	2	0	days/week
	f27	7	4	2	0	days/week
	f7	6	4	2	0	milpa, natural vegetation, market, family, social gathering places
	f28	5	3	2	0	Human energy & organic manure (5); Organic and Inorganic (3); Inorganic only (2); Mechanical energy (0)
	f29	5	3	2	0	No contamination (5); Low contamination (3); Medium contamination (2); High contamination (0)
	f8	10	5	2	0	Number of plants intentionally conserved
	f9	5	3	2	0	Always (5); Sometimes (3); Rarely (2); None (0)

*Variable; **f1: Plant resources; f2: Animal resources, f20: Number of strata, f21: Number of life forms, f3: Number of management zones, f4: Number of use categories exploited by the family, f22: Use and availability of food in HG (months), f5: Total number of individuals/m2 -Biological activity of edaphic macrofauna, f23: Frequency of water availability, f24: Distance to water bodies, f25: Pest observed in plants, f26: Disease observed in animals, f6: Frequency of garden management activity, f27: Frequency of animal management activity, f7: Number of places within and between communities connected, f28: Type of energy, f29: Agrochemical used (type of inputs), f8: Local crops, varieties and breeds conserved, f9: Local crops, varieties and breeds information documented.

This proposition was based on a literature review relevant to evaluating the resilience and sustainability of agroecosystems (e.g., Masera, Astier, and López-Ridaura, 2000; Córdoba *et al*., 2020). A total of 15 indicators and 32 variables were employed to obtain the information necessary to detect the weak and strong components of homegarden resilience (appendix 2, 3, and 4). According to Sarandón and Flores (2014), an indicator is a variable selected and quantified that clarifies a trend that is not easily detectable otherwise. Quiroga Martínez (2001) states that an indicator is a variable that depends on the value it assumes at a given moment, displays meanings that are not immediately apparent. Variables are a logical grouping of attributes or characteristics that define an observed phenomenon. In other words, it is a characteristic observable that can take different values or be expressed in several categories (Ander-Egg, 2004).

Also, as specified by Sarandón (2002) and Cáceres (2008), the indicators were selected based on the attributes of the studied system (i.e., based on states approach at the moment instead of process approach indicators) that meet the following characteristics: a) they were easy to obtain and interpret by the owners of the gardens themselves; b) they provide and synthesize good information; c) they analyze the same series of data in time and space; d) they were expressed in equivalent units through appropriate transformations based on a qualitative scale; e) they have universal characteristics but adapted to each particular condition; f) they were adequate to the objective pursed as well as related to sustainability requirements.

2) Data collection

The data relevant to this research was gathered during the period of June 2018-July 2019. Before the information gathering, the consent of the owners of the households was obtained after exposing the objectives and scope of the research. In addition, volunteers from the community participated as translators (of Spanish and Totonac) during the data collection process. Both qualitative and quantitative methods were applied to obtain information relevant to the adopted ecological, economic, and sociocultural indicators in this study.

Table 17. Performance criteria matrix of economic and sociocultural variables.

Component	Variable*	Range of values to resilience (R)				Criteria
		High R	Medium R	Low R	None	
Monetary gains	f10	100	50	25	0	Percentage of income
	f11	100	50	25	0	Percentage of savings
Organizational capacity	f12	6	4	2	0	days/week
	f13	5	3	2	0	Number of activities
	f30	5	3	1	0	Number of services
	f31	5	3	2	0	Owner with a land title (5); Owner with land title from a peasant organization or collective property (3); Renter (2); None (0)
	f14	3000	1000	500	0	m^2
	f15	5	3	2	0	All members speak (5); Children only understand not talk (3); Adults only (2); None (0)
	f16	5	3	2	0	Number of activities
	f17	5	3	2	0	Excellent (5); Fair (3); Poor (2); Very poor (0)
	f18	5	3	2	0	Excellent (5); Fair (3); Poor (2); Very poor (0)
	f19	4	2	1	0	Number of generations
	f32	20	10	5	0	Number of forms of preparation or utilization of plants known

*f10: Perception of income from HG products, f11: Perception of savings for self-consumption, f12: Family participation in management activities of HG, f13: Family participation in community activities and religious festivals, f30: Access to drinking water, light, health, education, telecommunication services, f31: Land ownership; f14: Size or area of the property, f15: Practice of native language, f16: Use of native dress, the practice of traditional dance or song and participation in religious activities, f17: Degree of knowledge of third-generation about traditional food and the resources used, f18: Knowledge of land-use practices and associated biological resources and cosmology transmitted from second to successive generations, f19: Number of generations continue practicing HG for subsistence and income, f32: Knowledge of plant use.

For example, ethnobotanical exploration, semi-structured interviews, surveys, direct and participant observation were employed to gather the data sets of information. Plant inventory in the gardens was made. The ecological variable of edaphic macrofauna was evaluated in the study units using the standard line transect method of the International Program of Biology and Fertility of Tropical Soil (TSBF) was followed by studying soil monoliths of 25x25x30 cm and the extraction of the fauna manually *in situ* (Anderson and Ingram, 1994; Cabrera *et al*., 2017). The species were identified using literature review (photos) and consulting with experts.

3) Assigned weightings for components, indicators, and variables of HG agroecosystem

To operationalize the resilience measurement of HGs, this study assigned the weighting coefficients to the employed components, indicators, and variables (appendix 2, 3, and 4), through consultation with owners of gardens (after explaining the meaning of resilience) as well as the experts from several disciplines (such as ethnobotany, economy, and ecology) using Delphi method.

The weightings were distributed to each selected component, i.e., agrobiodiversity (0.30), management and conservation capacity (0.25), monetary gains (0.20), and organizational capacity (0.25) due to its importance to building the resilience of homegardens by maintaining its basic structure and function to withstand adverse changes. In other words, although all the components have equal importance to building resilience and sustainability, agrobiodiversity was given more importance than other components, especially monetary gains (which has only 20). This is mainly due to the fundamental role of endowments (in this case, diversity of crops and animals) in an agroecosystem to operate other components, including monetary gains.

4) Assigned score to all variables using a 5-point ordinal categorical scale

All the 32 variables were categorized based on the established criteria to assign values using an ordinal categorical scale (appendix 2, 3, and 4). The coded values (from 1 to 5, where 1 represents the lowest level of resilience and 5 expresses the highest level of resilience) mainly compare the homegardens in an amoeba diagram and develop a resilience score index (RI) to measure the current degree of its resilience. This methodological strategy has been employed and validated in other studies (Toro, Requena, Duarte, and Zamorano, 2013; Arrieta, Requena, Toro, and Zamorano, 2016; Martínez, Toro, and León, 2018; Córdoba *et al*., 2020). In addition, it helps to avoid arbitrariness or subjective application of indicators and integrates all variables into an index. The values were applied based on semi-structured interviews, expert opinion, and literature review.

5) Developed threshold values of performance to all variables to sort HGs resilience

The limiting or threshold values of performance were assigned to all variables of each component to categorize under high, medium, and low resilience profiles. The coded values were based on different criteria mentioned in table 16 and 17. All variables had maximizing criteria value for the category of high resilience, except f24 (distance to water bodies), f25 (number of plants affected by pest), f26 (percentage of animals affected by some disease). The established limits of each variable are mainly to determine the categories of HGs using multi-criteria decision (sorting) analysis of PROMETHEE (Preference Ranking Organization Method for Enriched Evaluation).

6) Elaboration of the resilience score index (RI)

Each component is estimated separately to generate a composite index of homegarden resilience. As the four components have a specific set of indicators, they were combined and weighted to develop an overall index called the “resilience score.”

As mentioned earlier, the values of the variables were coded on an ordinal categorical scale in which a maximum of five points was assigned to each variable to develop the resilience index.

For each orchard, the values of the indicators of each component were calculated with the formula

$$I_i = \sum_{j=1}^{m_i} \frac{q_{ij} V_{ij}}{5}$$

Where

I_i =indicator value i; m_i = number of variables in indicator i; q_{ij} = weight of variable j within indicator i; V_{ij} = Coded value of variable j within indicator i.

For each indicator, a comparison of proportions (p = 0.05) was made (Gil and de Lara, 2008) between the component values obtained in each of the 12 orchards. Radial graphs were created from the coded values of each indicator, considering the four components. The charts were compared to identify orchards with similar characteristics.

For each garden or orchards, an index for each component was calculated from the formula

$$C_i = \sum_{j=1}^{n_i} \frac{q_{ij} V_{ij}}{5}$$

Where

C_i = índex of component i; n_i = number of variables in component i.

q_{ij} = weight of variable j within component i; V_{ij} = coded value of variable j within component i.

A comparison of proportions (p = 0.05) was made between the component indices obtained in each of the 12 orchards for each component. Subsequently, the resilience index was calculated for each orchard using the following formula:

$$R = \sum_{i=1}^{4} w_i C_i$$

Where

R = index of resilience; w_j = weight of component i; C_i = index of component i.

A comparison of proportions (p = 0.05) was made between the resilience indices obtained in each of the 12 gardens.

7) Evaluation of HGs sustainability based on its category of resilience

To assess the sustainability of homegardens, based on their degree of resilience, multi-criteria decision (sorting) analysis was performed. As resilience is the fundamental property of sustainability, this research proposed that homegardens with a high degree of resilience represent potentially sustainable than a medium (average sustainable) and low (potentially unsustainable) degree of resilience. In other words, we suggest that, Sustainability of HGs = HGs with a high degree of resilience. Therefore, this research utilized the FlowSort method to categorize the gardens into high, medium, and low resilience. Also, this method facilitates determining the desired outcomes or behavioral characteristics of the study units based on the established thresholds for each variable in each category.

The FlowSort method

The FlowSort method (Nemery and Lamboray, 2008), making use of the PROMETHEE methodologies (Brans and Vincke, 1985), computes the positive, negative, and net flow for each share x in $\dot{R}$, through equations (1), (2) and (3), respectively, where $\pi(x, y)$ denotes the preference of stock x over stock y.

As in the generality of sorting problems, the one we want to solve consists of the following elements:

A set of actions to be categorized $A = \{a_1, a_2, \dots, a_n\}$.

A set of performance criteria (Table 16 and 17) for the actions $F = \{f_1, f_2, \dots, f_m\}$

A group of reference profiles $R = \{r_1, \dots, r_{k+1}\}$, used to define each category, where $\dot{R}_i = R \cup \{a_i\}$is the extended set of profiles, considering each action a_i.

A group of preference functions (Brans and De Smet, 2016), which satisfy the decision-maker's preferences, is selected.

A set K of predefined categories $C_1, C_2, \dots, C_K$, where category $C_1,$ is the best and category C_K is the worst. Limit profiles or central profiles predefine each category. In the first case, each category is defined from an upper limit (r_j) and a lower limit (r_{j+1}). In the second case, the categories are defined by a central element or centroid (r_j^*). A set of weights associated with each criterion, $W = \{w_1, \dots, w_m\}$.

Where, $\sum_{m=1}^{q} w_{\mathrm{m}} = 1$.

Finally, to define the allocation of each share in the corresponding class, the allocation rules expressed in equations (4) and (5) are used. If there is a conflict between (4) and (5), the net flows are used (Sepulveda, Alfaro, and Vasquez, 2014).

$$\phi^{+}_{\dot{R}_i} = \frac{1}{|\dot{R}_\iota| - 1} \sum_{y \in \dot{R}_i} \pi(x, y) \qquad (1)$$

$$\phi^{-}_{\dot{R}_i} = \frac{1}{|\dot{R}_\iota| - 1} \sum_{x \in \dot{R}_i} \pi(y, x) \qquad (2)$$

$$\phi_{\dot{R}_i} = \phi^{+}_{\dot{R}_i} + \phi^{-}_{\dot{R}_i} \qquad (3)$$

$$C_{\phi^+}(a_i) = C_h, if \phi^{+}_{\dot{R}_i}(r_h) \geq \phi^{+}_{\dot{R}_i}(a_i) > \phi^{+}_{\dot{R}_i}(r_{h+1}) \qquad (4)$$

$$C\ \ ^{-}(a_i) = C_h, if\, \phi^{-}_{\dot{R}_i}(r_h) \geq \phi^{-}_{\dot{R}_i}(a_i) \leq \phi^{-}_{\dot{R}_i}(r_{h+1}) \qquad (5)$$

In other words (Ishizaka and Nemery, 2013), what FlowSort does is prioritize the set $\dot{R}_i$ for each a_iAnd the two profiles r_h and r_{h+1}, among which a_iIs positioned, identify the class to which that is assigned.

4. Results and Discussion

4.1. General characteristics of Totonac HGs

Totonac homegardens are human-made agroecosystems combined with multi-strata vegetation structures and animals near the individual home surroundings. Their boundaries were either fenced or delineated using plants. Most of the houses in the study area were made of concrete, and gardens are found in the backyard. Houses were divided into different sections that include rooms, kitchens, and lavatories. Other types of structures such as barns and sheds are found in the study units used to store food harvest, firewood, or other materials and sometimes as stables for livestock.

The owners owned all the study units. They were managed mainly by the members of the smallholder farming families using traditional knowledge embedded in their culture regarding local environmental conditions and natural resources. Although both men and women participated in the management activities (such as weeding, harvesting, irrigating, sowing, clearing branches, caring for domestic animals) of the homegardens, women played a crucial role in the decision's regarding species composition and structural arrangements within gardens. Also, most of them are about 30 years old.

The primary function of these homegardens is the production of multiple products (such as staple food, vegetables, fruits, spices, medicines, ornaments, wood, handicraft, ritual materials) for subsistence; this is, to meet the daily needs of the household. However, the excess production in some families is either exchanged with neighbors or sold in the local market to earn additional cash income.

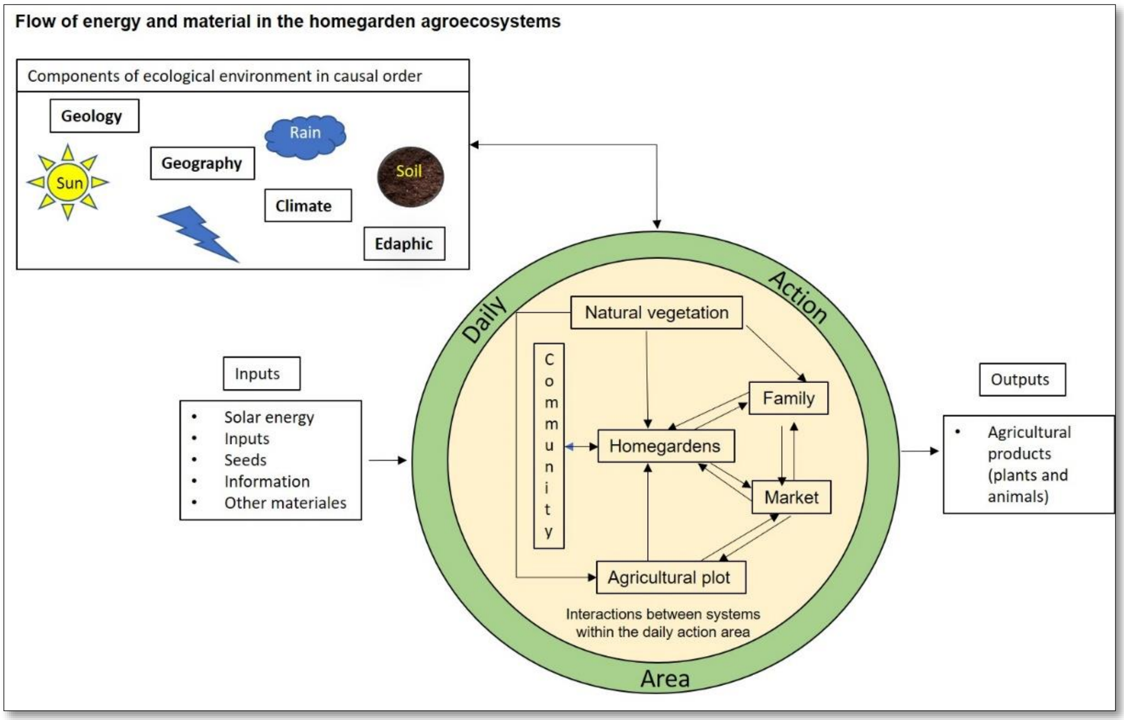

Figure 25. The flow of energy and material in homegarden agroecosystems. (Source: Elaborated by the authors).

According to the garden owners, both the plant diversity and the garden size had decreased since 1998 due to several reasons: fragmentation of land for construction purposes, lack of family labor, the advanced age of the owners, change in owner's preferences, etcetera. Currently, the size of the homegarden varies between 100-3000 m^2, and the average homestead area is 300-500 meters. The age of homegardens was varied between 5-30 years. However, age was not determinant in the diversity. Some other characteristics such as low external inputs, low capital investment, using manual power energy are not changed significantly in the study units except few units. This is due to the cultivation of the coffee plant for commercial purposes. In all cases, pigs were kept in small corals within the garden, and chickens were freely roaming in some cases, while in others, they were kept in the closed stables. Thus, the energy flow of the homegarden agroecosystems in the study site was almost similarly interconnected with other subsystems in the daily action area within other communities (Figure 25).

Most of the observed above general characteristics regarding the physical and socio-economic aspects of the study units resembled other studies of HGs from different parts of the world, including Mexico (Kumar and Nair, 2006; Mariaca, 2012; Galhena *et al*., 2013; Krishnamurthy *et al*., 2017; Ordoñez Diaz *et al*., 2018). However, the existing differences in the whole dynamics of these traditional agroecosystems in the study area depend on both ecological and cultural aspects that are reflected in the management, use, and conservation of the agrodiversity components (agrobiodiversity, management, and conservation capacity, monetary gains, and organizational capacity) associated with homegardens.

Moreover, the changing rainfall patterns, drought, and the wind were often mentioned (information obtained based on the memory of the elders above 50 years) as the frequent meteorological variations that had a high probability of occurrence and high impact in the last 30 years (1998-2018) in the study area. However, this study observed that these climatic variations did not significantly affect the structure and functions of homegardens compare to other land-use practices. Also, the migration and acculturation processes were considered a significant impediment to continuing the activities relevant to traditional land-use agricultural practices, including HGs.

Currently, a lot of traditional homegardens in the study area are changing due to many factors. Consequently, the transformation in the agrodiversity components is inevitable. Although the owners of the study units still consider homegarden as a traditional and vital practice for subsistence and livelihood, two owners are not giving enough attention due to lack of time. Furthermore, four gardeners cannot continue due to their advanced age and lack of family labor (as other adults and youngsters migrated to other parts in search of better opportunities).

4.2. Component index of HGs

4.2.1. Component and indicators of Agrobiodiversity

Overall, regarding agrobiodiversity (ABD), the orchard H4 presented the highest value, while H8 presented the lowest value. This may be due to the family members' interest and cultural preferences to diversify the products (plants and animals) in the garden and their frequent participation in the garden management activities. On the other hand, the lowest value obtained by H8 is mainly due to the garden size, the advanced age of the owner (95 years old), lack of labor as the family members migrated to other parts of Mexico.

Regarding the agrobiodiversity indicators (Figure 26), as in species diversity, differences are only seen from orchards H2 and H4, which significantly exceeded H8. Although a total of 101 species, 93 genera, and 45 families of plants were documented from the Totonac HGs in the study area, the number of plant species in each homegarden ranged only from 20 to 49. And about 65% of the gardens contain 32 to 49 plant species, while very few orchards have less than 30 species. However, these results differ with Van Der Wall and Bongers (2013), who found species richness of nine to 54 species in a sample of 61 homegardens in Tabasco, with an average of 22 species per orchard. Another study by Castañeda-Guerrero, Aliphat-Fernández, Caso-Barrera, Lira-Saade, and Martínez-Carrera (2020) in a sample of 60 Totonac homegardens in Caxhuacan showed that the range of plant species varied from six to 82 average of 40 species per garden.

The most commonly represented families in the study area were Amaranthaceae, Anacardiaceae, Araceae, Arecaceae, Apocynaceae, Begoniaceae, Compositae, Cucurbitaceae, Euphorbiaceae, Fabaceae, Lamiaceae, Malvaceae, Myrtaceae, Nyctaginaceae, Piperaceae, Poaceae, Rosaceae, Rutaceae, Rubiaceae, Solanaceae, and Zingiberaceae. Many of the above families are intentionally cultivated and conserved in the study area. It is mainly because of the multi-functional feature of these crops and their popularity in the Totonac culture as food and medicinal sources or for other uses.

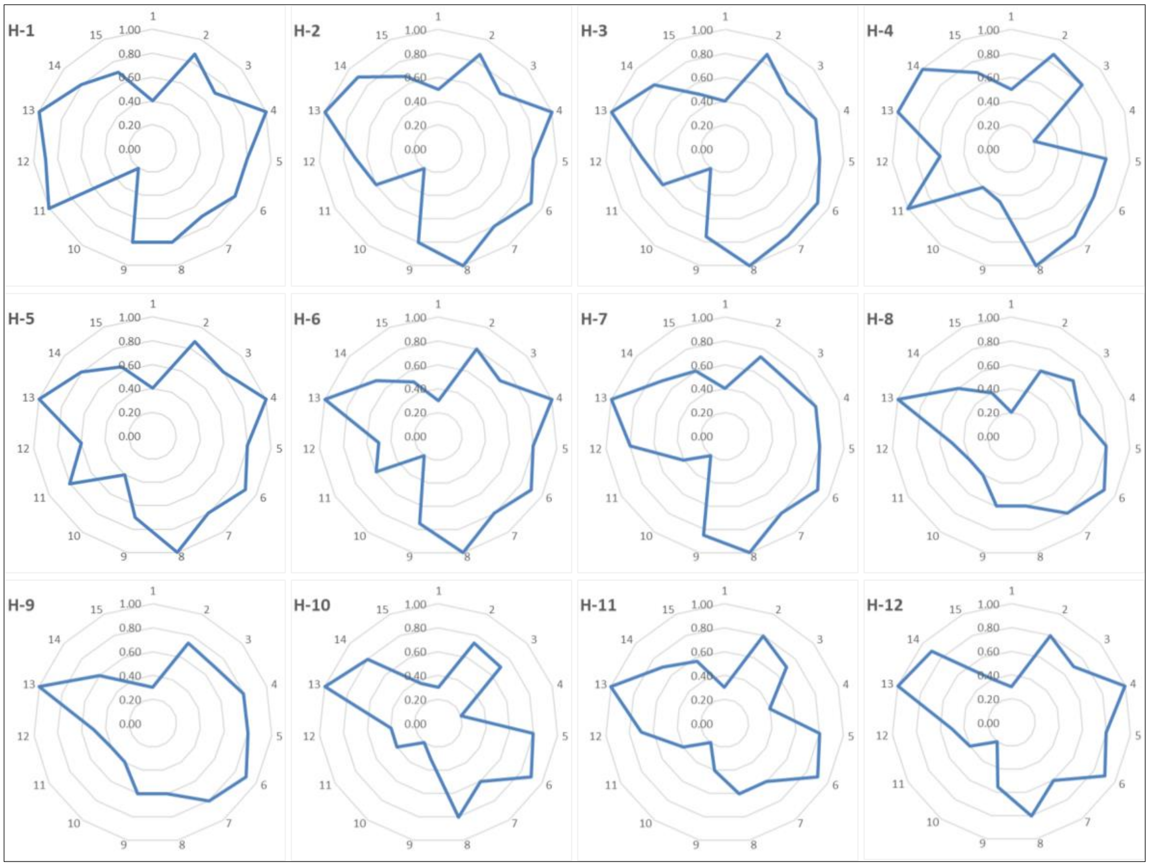

Figure 26. Values obtained for 12 orchards in each indicator: 1) Species diversity, 2) Structural diversity, 3) Functional diversity, 4) Soil quality, 5) Water availability, 6) Pest management, 7) Labor activities, 8) Daily action area, 9) Conservation practices, 10) Level of income, 11) Level of savings, 12) Family participation, 13) Access to public services, 14) Land tenure, 15) Transmission of local biocultural knowledge.

Five animal species belonging to four families and five genera were found in the study units. The most common animals domesticated in the study units were pigs (*Sus scrofa*) and backyard birds such as chickens (*Gallus gallus domesticus* L.), turkeys (*Meleagris gallopavo* L.), ducks (*Carina moschata* L.), geese (*Anser anser* L.). This coincides with previous studies on traditional land-use practices of homegardens in many parts of Mexico (Mariaca, 2012; Ruiz-Nieto, Espinosa-Trujillo, Mireles-Arriaga, Isiordia-Lachica, and Hernández-Ruiz, 2019). In summary, both the frequency and abundance of certain plants and animals indicate the cultural as well as functional importance of these species.

H8 presented the lowest value for structural diversity, although it was not different from gardens 7, 9, and 10. Regarding the number of strata, the majority of the gardens are distributed vertically with four layers of vegetation (0-1 m of herbaceous plants; 1-3 m of shrubs; 3-5 m of medium-sized trees; above 5 m of tall sized trees) except garden 8 (with three layers).

The above results concur with other authors (Fernandes and Nair, 1986; Caballero, 1992; Lope-Alzina and Howard, 2012; Krishnamurthy *et al*., 2017;) who found that most of the homegardens are distributed vertically with at least three layers: lower levels contained herbs and food or medicinal plants (0-2 m), intermediate levels have shrubs or bushes and young, low trees (3-5 m), and upper levels contained tall trees (5-10 m). However, our findings differ from the study by De Clerck and Negreros-Castillo (2000). They identified six layers or strata in Mayan-Yucatecan homegardens in the state of Quintana Roo in Mexico.

All study units had all four (herb, trees, shrubs, and other) life forms regarding the number of life forms. However, herbaceous species dominated the different growth habits, which coincide with Krishnamurthy and Ávila, 1999; Krishnamurthy *et al*., 2017. Regarding the number of management zones, Totonac HGs were distributed into seven zones compare to the ten management zones recommended by Méndez (2000). The minimum zones were presented in orchard 8.

The above results resembled other studies (Mariaca, 2012; Chablé-Pascual, Palma-López, Vázquez-Navarrete, Mariaca-Méndez, and Ascensio-Rivera, 2015) that identified mixed zones of fruit trees, ornamental plants, herbaceous crops, shade trees, residence area, animal sheds. Also, these studies mentioned the irregular arrangements of management zones without any specific design like Totonac homegardens.

It is observed that there was no significant difference between HGs for functional diversity. This is because the use categories mentioned in each garden varied between the minimum range of 9-12. And about 50% of the study units exploited more than ten use categories out of 13 classified in this study. The most dominating use categories in plant species were ornamental use (43.56%) followed by food (39.6%), medicine (39.6%), sustenance (14.85%), spice (13.86%), fodder (7.92%), utensils (5.94%), beverages (5.94%), handicrafts (4.95%), ceremonial (4.95%), wood (3.96%), fuel (2.97%), and fiber (0.99%).

Besides, more than 80% of the owners indicated that food, spice, and beverages obtained in the orchards were utilized on almost a daily basis. Although members of the households generally agree that HG products are available throughout the year, the results showed that the availability and use of food (derived from both plants and animals) in homegardens varied between 7-9 months.

Even though climatic variations did not affect the structure and function of homegardens directly, irrigation of water in the gardens during the drought period (April, May, June) depends heavily on the owner’s management choices. Also, dietary changes, cultural values, occupation, illness, and age of the household members influence the use, and availability of food from the study units, thereby its productivity.

Regarding the functions of animals, they were kept to acquire either meat or egg products for family consumption. Also, these animals were slaughtered to prepare some traditional foods during religious festivities. Occasionally, animal products were sold to earn additional income to improve the family economy.

4.2.2. Component and indicators of management and conservation capacity

For the management and conservation component, orchards 1, 2, 3, 5, 6, and 7 stand out, with the highest values, while H10 and H11 were lower. In the management and conservation indicators, no differences were found between orchards for water availability. This is mainly due to the frequent access and the short distance covered from the garden to reach the water bodies.

No differences were found between orchards for pest management too. It suggests that the high plant diversity of the gardens might provide pest resistance or control. Also, agrochemicals were applied to deal with pest issues, particularly for the coffee plantations in some units. No disease was observed in the animals except in the chickens of orchard 1, which is minimum. The cause was not clear; however, the affected chickens were maintained in the closed space, and less attention was given to these animals due to the occupation of the garden's owner.

In the soil quality indicator, HGs 1, 2, 5, and 6 stand out. It is mainly because of incorporating previous plant residues, food waste from the kitchens, and manure of the roaming animals in the gardens. Some gardens, such as 4, 10, and 11, reported a low number of individuals, either due to the excess use of agrochemicals or lack of nutrients in the soil.

For labor activities, H3 and H4 presented the highest values. This is due to the daily attention given (i.e., at least one or two hours per day) by the family members (mainly women and children) to the gardens, particularly to the animal care activities (such as feeding, washing the stables, etcetera). Due to their occupation, time, age, and preferences, others dedicated a few days (that varied between 1 – 5 days) per week in the garden management activities.

For the daily action area, gardens 2, 3, 4, 5, 6, and 7 surpassed orchards 8, 9, and 11. This lower value is mainly because some owners did not possess an agricultural plot in the mountain. Therefore, their daily action area is reduced between garden, family, market. Also, the occupation, age, and illness of these owners have a significant influence on it. The rest of the owners of the study units are interacting with all the five places of the daily action area due to their frequent visits to the natural forest and thereby diversify their sources and permit them to transmit and exchange knowledge with others.

More interaction of family members in different places of the ecological environment increases the possibility of meeting most of their subsistence or livelihood needs. Also, the constant interaction between humans and nature increases the probability of identifying the potential anthropocentric use and conservation of native wild species. This coincides with Cuevas (1991), who stated that the more frequently visited by the people, the greater their knowledge of the ecological environment. And the more area covered by the people will reduce the extraction of species (for example, medicinal plants, fuelwood species, etc.) in a particular habitat.

In conservation practices, orchard 7 had the highest value, although it did not exceed H1 and H2. Consistently, H10 and H11 had lower values in the management and conservation indicators where there were differences. This lower value is mainly due to the application of agrochemicals for coffee plantations, which is also reflected in the evaluation of edaphic macrofauna, and therefore has high contamination.

Also, more than 40% of the households rarely registered some information regarding plantation and harvest details. However, not all the members of these households were aware of the information documented. Other owners did not record any information relevant to plants or animals due to lack of education or interest. And their knowledge is based on oral communication and memory. The results showed that only 25% of the households occasionally registered the information relevant to the local crops, varieties, and breeds. This is mainly due to the personal interest of the owners.

However, according to the results, the members of the other study units conserved specific agricultural biodiversity due to its multifunction or cultural importance. The number of crops or varieties conserved varied between four to seven based on the household members' preference. Although other crops are preserved in the gardens as *in situ*, the main crops mentioned frequently by the owners were (beans, chile, coffee, corn, garden ginger, orange, pumpkin or calabash, palm or pacaya, starleaf begonia, tomato, tomatillo. The conservation of plant genetic resources is essential to maintain and increase biocultural diversity and human well-being. In summary, Totonac HGs, in general, possess high agrobiodiversity (i.e., species, structural, and functional diversity) and contribute to increasing the ecological resilience of homegardens. However, the conservation practices are deficient in some units and require more capacitation to improve them.

4.2.3. Component and indicators of monetary gains

No differences were found between orchards for income level, an indicator of monetary gains. This is because homegarden products were mainly used to meet the family's needs, i.e., self-consumption. Although the excess products were occasionally sold or exchanged either in the local market or between the neighbors, the income from these products was not stable or uniform and sufficient to meet the family's monetary needs. And all the study units perceived that the HG products' revenue was low and very low. The approximate income or economic support per week reported by the study units varied between 700 to 1500 pesos.

Even if homegardens were recognized as less productive (in terms of income) compared to other agroecosystems, the potential of HGs to provide additional income is undeniable. Moreover, according to Turrent, Wise, and Garvey (2012), traditional systems such as milpa with compound crops can be more productive, particularly in crises (such as pandemics of Covid 2019) and conflicts (such as war). It is also indisputable that high or low income based on productivity of an agroecosystem depends on several factors such as product diversification, market price, infrastructure, management, value addition to the production.

Therefore, the monetary gain component differences correspond to savings, where orchards 1 and 4 presented the highest levels. Saving here refers to the amount of money not spent on consuming food, medicine, or other garden products. In other words, it relates to the use-value of homegarden products. However, the owners of the six study units mentioned that savings from homegarden were low. It is mainly because of the age and illness of the owners who were unable to participate actively in the management to diversify HG resources. Other units reported that savings were medium and high due to their high consumption of plants and animals from the HGs. Also, most study units' approximate amount of cash spent on food per week varied between 200 and 500 pesos. Dietary preferences in some units significantly influenced the amount spent on food.

The above results at some degree coincide with the study of Guadarrama and Hernández (1981), who reported that the use-value of products from traditional agroecosystems such as homegardens was high and cannot be reflected in the calculation of conventional economics, as farmers who manage these systems take advantage of the resources provided by the natural environment throughout the year, from their orchards and agricultural plots to cover their basic needs compare to modern farming systems. Besides, the value of positive externalities such as ecosystem services was not probably considered by the owners when they expressed their perception of savings for HG's self-consumption. Thus, the indirect monetary values in these agroecosystems are considerably high.

In summary, the generated income from the surplus products derived from Totonac HGs in the study area is minimal compare to the savings of money due to the consumption of products from the family orchards. However, most families who possess HGs in the study area still live under poor conditions that significantly contribute to higher poverty levels and malnutrition, especially among children. Furthermore, although saving money by exploiting the goods and services from the orchards significantly contributes to increasing economic resilience, the family's monetary needs are not met by the land-use practice of HGs and therefore contribute to reducing its economic resilience.

4.2.4. Component and indicators of organizational capacity

In the organizational capacity component, orchards 1, 2, and 4 stands out, unlike orchards 8, 9, and 10, which presented the lowest values for this component. In the indicator of access to public services, the organizational capacity component gave the maximum value in all the HGs. This is because all the study units had access to public services such as drinking water, electricity, education, telecommunication, and health services. It indeed guarantees the well-being of the family members of the study units to participate in the homegarden practice.

Also, the availability of essential services a universal and social right of every individual) ensures equality, education, and social justice. However, this also influences the cultural erosion significantly, as preferences of youngsters regarding diet, occupation, etcetera are changing in the study area, which may represent an abandonment of agricultural activities shortly. This concurs with Benz, Cevallos, Santana, Rosales, and Graf (2000) indicate that the effects of the modernization process, such as quality of housing and literacy, significantly influence the erosion of traditional knowledge in some communities in the Sierra de Manantlan of western Mexico.

For the indicator of family participation, H1 had the highest value. This is because, in most study units, children rarely participated in the management activities of the homegarden. Thus, it indicates that there is a lack of interest of children to continue the homegarden practice. However, other studies state that family labor (mainly women and children) is one of the essential characteristics of traditional agroecosystems such as HGs in other parts of the world, including Mexico (Kumar and Nair, 2006; Mariaca, 2012; Krishnamurthy *et al*., 2017; Ordoñez Diaz *et al*., 2018).

In the land tenure indicator, H4 stands out without being significantly different from H2. The type of tenure is an important indicator, as it influences the decision-making in the processes of management, use, and conservation of land linked to agricultural activities. All the interviewees mentioned that they owned the title of the property. Therefore, it allows them to make their own decisions based on their preferences without any external influences.

Regarding the size of the property of the study units, it varied between 100-3000 m^2, and the average homestead area is 300-500 m^2. The age of homegardens ranged between 5-50 years. However, the observation of the units indicated that the size of the property did not influence the diversity of gardens. Although tree species such as cedar, jonote represented the importance of the garden’s age.

For the indicator of transmission of local biocultural knowledge, orchards 1, 2, 4, 5, 7 had the highest values compare to others. In contrast, the lowest values were registered in gardens 8, 9, 12. In other words, although orchards 1 and 4 presented the highest values, they did not substantially exceed orchard 2. This is mainly due to the lack of transmission of knowledge to the young or future generations. For example, in more than half of the study units, the language was practiced only by adults and no longer practiced by the younger generation. It indicates that adults still preserve their cultural heritage. Still, it was not transmitted to present generations, which is probably due to the last century's indigenous policies that influenced the social rejection of native people at a certain level. The above coincides with Oliveros and Islas (2017), that reported that the Hñathö or Otomi language in Michoacán is at risk of disappearing due to the long historical and social process of discrimination, exclusion, and racism.

Besides, as the use, management, and conservation of natural resources is linked with the holistic worldview of the native people, and it is crucial to assess the persistence of traditions, customs, and religious practices by the members of the study units. The results showed that older people in 50% of the study units (gardens 3, 5, 6, 8, 9, 10, 12) still prefer to wear and proudly use the traditional costume. Also, as the young and adults of these units migrated to another community or state, the older people are managing the homegarden.

Moreover, young people, as well as grandchildren of the above units, have stopped wearing this clothing may be due to social rejection. Besides, to some degree, they were not familiar with spiritual-religious celebration practices associated with agricultural calendars as they migrated from their native place. Therefore, it indicates the process of acculturation, which directly impacts. Also, family members' participation in community activities and religious festivals is vital to transmitting knowledge associated with the agricultural calendar. However, the results indicated that few units (25%) always participated in this activity. On the other hand, others were often or sometimes participated in the events, except garden H10. This is mainly due to the illness of the household head.

Notably, gardens 2, 4, 5, 7, 11 follow at least two (traditional songs and dance or dress traditional dress). This is mainly due to the children's participation in performing traditional dances and songs during religious festivals or school activities within the community. The members in garden one still follow all three activities. This is due to the adults' belief in family tradition or inheritance. However, children and young people in this unit showed a lack of interest in continuing all the customs, and currently, they are just following the elder's instructions.

Children in the H1 showed a high degree of knowledge relevant to plants' use, mainly due to their interactions with their grandmother Mrs. Carmen who constantly communicate about plant uses in the native language. Also, about 25% of the study units showed poor knowledge, as there was no third generation present in the community either due to their migration or lack of children. It indicates the process of acculturation and uprooting that significantly impacts the conservation of local biocultural heritage unless documented and promoted through ethnobotanical or community gardens. This concurs with Benz *et al*. (2000), who reported that the traditional knowledge about plants suffered a decline that accompanied the loss of the indigenous language in some communities in the Sierra de Manantlan of western Mexico.

However, compared to knowledge about plant use and traditional food, the children from the 50% of the study units showed poor knowledge relevant to management practices in agroecosystems and associated ecological knowledge (local flora and fauna). This is mainly due to the lack of interest as well as the gap in transmission of knowledge. However, the rest of the study units' degrees of expertise varied from fair to good.

Moreover, about 7 out of 12 study units had just one generation, i.e., the current generation formed only by elders (father) to practice this traditional land-use activity. And the rest of the units (gardens 1, 2, 3, 4, 6) have two generations (father and son) who continue this practice. However, the third generation (grandchildren) of these units was not showing any interest in continuing HG practice either due to lack of motivation or preference to migrate.

Regarding plant use knowledge, the head of the study units stated different forms of preparation or utilization of various local resources (plants and animals) in the surrounding environment (including homegardens). The number of forms or ways frequently mentioned varied between 16-20 forms of use, including food, medicinal, ritual, and other benefits (appendix 1). The various forms of use or exploitation of local resources by the owners contribute to their conservation and sustainability.

In summary, despite several internal shocks such as migration, illness, or death, the traditional land-use practice of homegardens is still prevalently practiced by the first and (in some units) second generation of an indigenous group Totonacs basically for self-subsistence, i.e., for family consumption. However, as owners of many units are older people with illness, continuity of this traditional practice by the third or new generations remains doubtful mainly due to the existing gap in the transmission of knowledge and migration to satisfy economic needs, which in turn contributes to diminishing the sociocultural resilience of these systems.

4.3. Resilience score index of HGs

An index is a combination of indicators into a single score. The highest resilience index was found in orchards H1, H4, and H5, followed by orchard H2 (Figure 27). Garden H1 was characterized by having values within the highest statistical group in the four components. This indicates that the agrodiversity of H1 was high compare to the rest of the HGs. Although the overall index of H1 was high (based on the aggregation of performance of all components), it is crucial to notice that not all the variables of H1 had a higher score (in this case, 5 for high resilience).

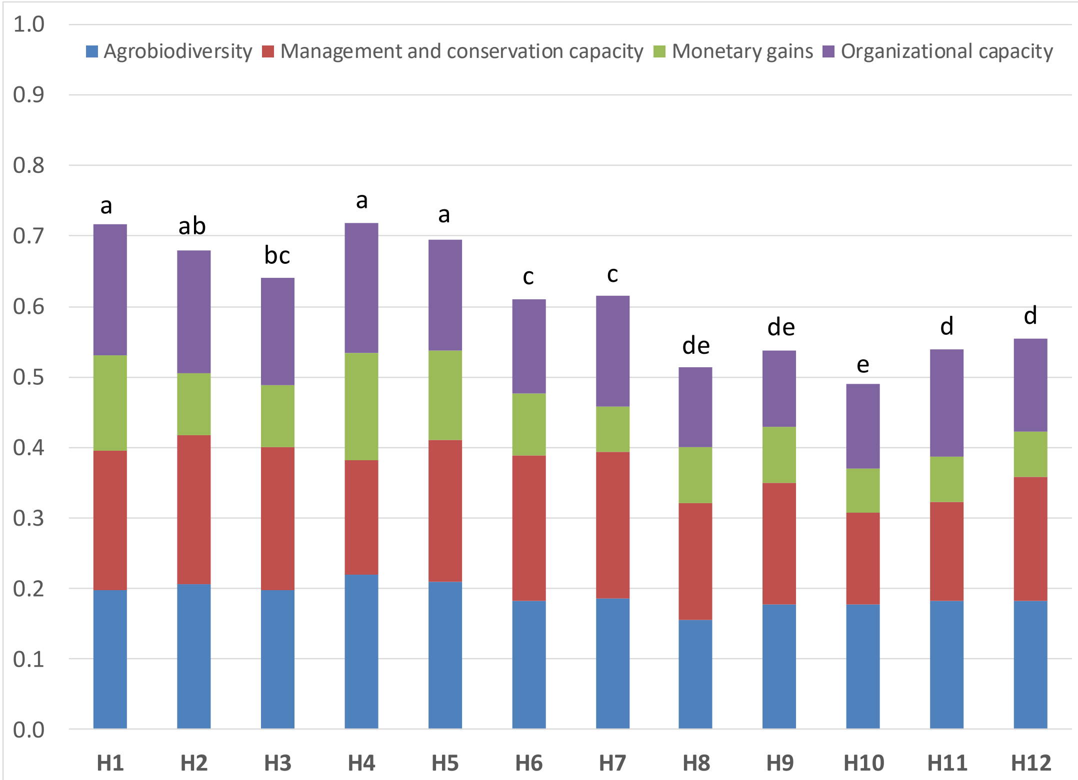

Figure 27. Resilience index of 12 orchards, based on a four-component weighted rating. Bars with the same letter are not different ($p \leq 0.05$).

In other words, in some variables, H1 got a low value (in terms of desired outcomes) established in the criteria. For example, regarding animal resources (one of the variables of species diversity indicator), H1 had only pigs and chickens, and the obtained score value was just two. Thus, in summary, although H1 got the higher rank because of its better performance compared to others, it does not signify that H1 had the 100% desired outcome or behavioral characteristics of resilient homegarden systems.

Also, it is essential to remember (when analyzing the overall performance of the study units) that both components and indicators were comprised of a group of variables, and the better performance of one of the variables might balance the negative performance of others within the group. For example, the low value (2) obtained for the variable of animal resources by H1 was balanced by the high value (5) obtained for the number of management zones within the component agrobiodiversity. The same above inferences explain the high value for specific components obtained by some units. For example, garden 4 presented the highest value of agrobiodiversity and was in the highest statistical group for two more components but showed intermediate values in management and conservation capacity. On the other hand, as we mentioned earlier, the low value in MCC is mainly due to the negative performance of conservation practices and soil quality indicators.

Figure 28. The landscape of Santiago Ecatlan.
(Source: Photo taken by the first author).

Orchard 5 was in the highest statistical group in three components but with intermediate values for organizational capacity. To be specific, some variables such as participation of members in activities of HGs (got two scores) and the number of generations (got just one score) had the lower performance. Orchard 2 also presented values in the upper range for three components but had intermediate monetary gains, where both income and savings were low.

Orchard 10 presented the lowest resilience index without being different from orchards 8 and 9. These three orchards were found in the lowest statistical group in three of the four components. They only differed in management and conservation capacity, where H8 and H9 had intermediate values, and H10 presented a low value. However, the performance of H11 and H12 surpassed gardens 8, 9, 10, with minimum differences. The lower performance of these HGs is mainly due to advanced age, illness, lack of family labor (because of migration). In H10 and the above factors, disease and lack of children to continue the HG practice significantly affect its resilience.

Table 18. The performance of homegardens and weights of selected criteria.

W	0.075	0.075	0.06	0.09	0.0625	0.05	0.0375	0.05	0.05	0.08	0.12	0.0375	0.025	0.05	0.025	0.0125	0.0375	0.0375	0.025
Homegarden	**f1**	**f2**	**f3**	**f4**	**f5**	**f6**	**f7**	**f8**	**f9**	**f10**	**f11**	**f12**	**f13**	**f14**	**f15**	**f16**	**f17**	**f18**	**f19**
H1	49	2	7	11	1000	2	4	5	3	1	5	4	5	3	5	3	3	2	2
H2	42	3	7	10	1000	3	5	6	3	1	3	2	5	4	4	2	3	3	2
H3	38	2	7	11	600	4.5	5	7	1	1	3	3	4	3	2	1	3	2	2
H4	47	3	7	12	100	5	5	7	1	2	5	2	4	5	5	2	3	3	2
H5	46	2	7	12	3000	3	5	6	1	2	4	2	4	3	3	3	3	3	1
H6	37	1	6	10	1800	3	5	7	1	1	3	2	3	2	2	1	3	2	2
H7	23	3	5	10	800	3	5	7	3	1	2	3	5	2	3	2	3	3	1
H8	22	1	4	9	400	3	3	4	0	2	2	2	3	1	2	1	2	1	1
H9	28	1	5	10	800	3	3	4	0	2	2	2	3	1	2	1	1	1	1
H10	39	1	5	11	200	1	4	4	0	1	2	2	2	3	2	1	1	1	1
H11	20	2	6	11	300	1	3	5	0	1	2	3	4	2	3	2	3	3	1
H12	32	1	6	10	1200	1	4	6	0	1	2	2	3	4	2	1	1	1	1

W: weights, f1: Plant resources; f2: Animal resources, f3: Number of management zones, f4: Number of use categories exploited by the family, f5: Total number of individuals/m2 -Biological activity of edaphic macrofauna, f6: Frequency of garden management activity, f7: Number of places within and between communities connected, f8: Local crops, varieties and breeds conserved, f9: Local crops, varieties and breeds information documented, f10: Perception of income from HG products, f11: Perception of savings for self-consumption, f12: Family participation in management activities of HG, f13: Family participation in community activities and religious festivals, f14: Size or area of the property, f15: Practice of native language, f16: Use of native dress, practice of traditional dance or song and participation in religious activities, f17: Degree of knowledge of third generation about traditional food and the resources used, f18: Knowledge of land-use practices and associated biological resources and cosmology transmitted from second to next generations, f19: Number of generations continue practicing HG for subsistence and income

4.4. Evaluation of resilient categories of HGs: FlowSort analysis

After collecting the information, Table 18 shows the set of alternatives, in this case, *Hn* homegardens, to be categorized and their performance in each of the 19 criteria (f1-f19) selected to qualify resilience, which they are all to be maximized. Although a total of 32 variables or criteria were proposed to build a resilience score index of HGs, only 19 criteria were considered in FlowSort analysis. This is mainly due to the notable differences in the performance values between study units of these variables to make pairwise comparisons between them, as others had similar values that make it difficult to compare between them in this analysis. However, this did not affect the overall results. Moreover, the results were almost similar to the results of the RI.

As a result of the weighting process, the importance of weights (w_k) assigned to each of the selected criteria are also presented. The registered performance for some criteria (e.g., f1-f8 & f19) are the quantitative values obtained. And the other criteria performance (e.g., f9-f18) is ordinal categorical score values utilized for qualitative data. On the other hand, Table 19 shows the limit profiles (r_i) defined to delimit the high, medium, and low resilience categories.

Table 19. Categories of resilience and limiting profiles.

Resilience	**R**	**f1**	**f2**	**f3**	**f4**	**f5**	**f6**	**f7**	**f8**	**f9**	**f10**	**f11**	**f12**	**f13**	**f14**	**f15**	**f16**	**f17**	**f18**	**f19**
	r1	80	10	9	15	900	7	5	10	5	5	5	5	5	5	5	5	5	5	4
High																				
	r2	40	5	7	10	400	4	3	5	3	3	3	3	3	3	3	3	3	3	2
Medium																				
	r3	20	2	3	5	200	2	2	2	2	2	2	2	2	2	2	2	2	2	1
Low																				
	r4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Smart-Picker software was used in the estimates of the FlowSort method. Table 20 presents the estimated results of the preference matrix where the global preference of each homegarden is observed, with respect to the set of limit profiles $\pi(Hn,rj)$. Likewise, the preference degrees of the limit profiles are presented with respect to each home garden $\pi(\ rj,Hn)$. All these values are between 0 and 1, and when the degrees of preference are similar and low (πij≈0≈πji), they are interpreted as that both alternatives are indifferent (Ishizaka and Nemery, 2013), this is the case, e.g., H2, H3, and H5, with the limit profile $r2$.

Table 20. The preference degree between HGs and limiting profiles.

Preference	$\boldsymbol{r_1}$	$\boldsymbol{r_2}$	$\boldsymbol{r_3}$	$\boldsymbol{r_4}$
$\pi(H1, r_j)$	0.0625	0.4725	0.7575	1
$\pi(r_j, H1)$	0.7675	0.2425	0.08	0
$\pi(H2, r_j)$	0.0625	0.325	0.87	1
$\pi(r_j, H2)$	0.875	0.255	0.08	0
$\pi(H3, r_j)$	0	0.315	0.72	1
$\pi(r_j, H3)$	0.9625	0.355	0.1425	0
$\pi(H4, r_j)$	0	0.5225	0.7575	1
$\pi(r_j, H4)$	0.7675	0.3175	0.1125	0
$\pi(H5, r_j)$	0.0625	0.46	0.7325	1
$\pi(r_j, H5)$	0.9	0.3175	0.05	0
$\pi(H6, r_j)$	0.0625	0.15	0.6325	1
$\pi(r_j, H6)$	0.9	0.5525	0.2175	0
$\pi(H7, r_j)$	0	0.175	0.7125	1
$\pi(r_j, H7)$	0.9375	0.5475	0.08	0
$\pi(H8, r_j)$	0	0	0.45	0.95
$\pi(r_j, H8)$	1	0.875	0.225	0
$\pi(H9, r_j)$	0	0.0625	0.45	0.95
$\pi(r_j, H9)$	1	0.785	0.2625	0
$\pi(H10, r_j)$	0	0.1275	0.3625	0.95
$\pi(r_j, H10)$	1	0.825	0.3425	0
$\pi(H11, r_j)$	0	0.115	0.4625	0.95
$\pi(r_j, H11)$	1	0.66	0.18	0
$\pi(H12, r_j)$	0.0625	0.2	0.45	0.95
$\pi(r_j, H12)$	0.9375	0.685	0.3425	0

It is interpreted as a preference when there is a high difference between the degrees of preference, $|\pi_{ij} - \pi_{ji}| \gg 0$, as the values observed between practically all homegardens and the profile r_1. A similar situation, where it can be interpreted as a clearly defined preference, is the case of all homegardens and the r_4 profile. No incomparability relationships are observed, that is, where both values between the orchards and the limit profiles are similar and significant, $\pi_{ij} \approx 0.5 \approx \pi_{ji}$).

Table 21. The positive, negative, and net flow scores for homegardens and category assignment.

Home garden	Flow	Limiting profiles r_1	r_2	r_3	r_4	Score	Resilience Category
	Φ^+_{H1}	0.9419	0.5606	0.2700	0.0000	0.5731	
$\dot{R}_1$	Φ^-_{H1}	0.0156	0.3681	0.6894	1.0000	0.2725	High
	Φ_{H1}	0.9263	0.1925	-0.4194	-1.0000	0.3006	
	Φ^+_{H2}	0.9688	0.5638	0.2700	0.0000	0.5644	
$\dot{R}_2$	Φ^-_{H2}	0.0156	0.3313	0.7175	1.0000	0.3025	High
	Φ_{H2}	0.9531	0.2325	-0.4475	-1.0000	0.2619	
	Φ^+_{H3}	0.9906	0.5888	0.2856	0.0000	0.5088	
$\dot{R}_3$	Φ^-_{H3}	0.0000	0.3288	0.6800	1.0000	0.3650	Medium
	Φ_{H3}	0.9906	0.2600	-0.3944	-1.0000	0.1438	
	Φ^+_{H4}	0.9419	0.5794	0.2781	0.0000	0.5700	
$\dot{R}_4$	Φ^-_{H4}	0.0000	0.3806	0.6894	1.0000	0.2994	High
	Φ_{H4}	0.9419	0.1988	-0.4113	-1.0000	0.2706	
	Φ^+_{H5}	0.9750	0.5794	0.2625	0.0000	0.5638	
$\dot{R}_5$	Φ^-_{H5}	0.0156	0.3650	0.6831	1.0000	0.3169	High
	Φ_{H5}	0.9594	0.2144	-0.4206	-1.0000	0.2469	
	Φ^+_{H6}	0.9750	0.6381	0.3044	0.0000	0.4613	
$\dot{R}_6$	Φ^-_{H6}	0.0156	0.2875	0.6581	1.0000	0.4175	Medium
	Φ_{H6}	0.9594	0.3506	-0.3538	-1.0000	0.0438	
	Φ^+_{H7}	0.9844	0.6369	0.2700	0.0000	0.4719	
$\dot{R}_7$	Φ^-_{H7}	0.0000	0.2938	0.6781	1.0000	0.3913	Medium
	Φ_{H7}	0.9844	0.3431	-0.4081	-1.0000	0.0806	
	Φ^+_{H8}	1.0000	0.7188	0.3063	0.0000	0.3500	
$\dot{R}_8$	Φ^-_{H8}	0.0000	0.2500	0.6125	0.9875	0.5250	Medium
	Φ_{H8}	1.0000	0.4688	-0.3063	-0.9875	-0.1750	
	Φ^+_{H9}	1.0000	0.6963	0.3156	0.0000	0.3656	
$\dot{R}_9$	Φ^-_{H9}	0.0000	0.2656	0.6125	0.9875	0.5119	Medium
	Φ_{H9}	1.0000	0.4306	-0.2969	-0.9875	-0.1463	
	Φ^+_{H10}	1.0000	0.7056	0.3356	0.0000	0.3600	
$\dot{R}_{10}$	Φ^-_{H10}	0.0000	0.2819	0.5906	0.9875	0.5413	Medium
	Φ_{H10}	1.0000	0.4238	-0.2550	-0.9875	-0.1813	
	Φ^+_{H11}	1.0000	0.6650	0.2950	0.0000	0.3819	
$\dot{R}_{11}$	Φ^-_{H11}	0.0000	0.2788	0.6156	0.9875	0.4600	Medium
	Φ_{H11}	1.0000	0.3863	-0.3206	-0.9875	-0.0781	
	Φ^+_{H12}	0.9844	0.6713	0.3356	0.0000	0.4156	
$\dot{R}_{12}$	Φ^-_{H12}	0.0156	0.3000	0.6125	0.9875	0.4913	Medium
	Φ_{H12}	0.9688	0.9375	-0.2769	-0.9875	-0.0756	

Table 21 shows the results of the estimation of the positive, negative, and net global flows for each extended set $\dot{R}_i$, where, for example, $\dot{R}_1$ is the set that includes homegarden 1, in addition to all the limit profiles, $\dot{R}_1 = R \cup a_1$. The rest of the homegardens are presented similarly. Since the global flows summarize the degrees of preference ordered in a unique score for each alternative, the net flow is the value that determines the category to which each garden belongs.

Under this, we observe that the H1, H2, H4, and H5 orchards belong to the high resilience category, while the rest belong to the medium resilience category. If we observe between which values of r_i, i.e., the value of the net flow of the garden analyzed falls, and it can be easily deduced to which category it belongs.

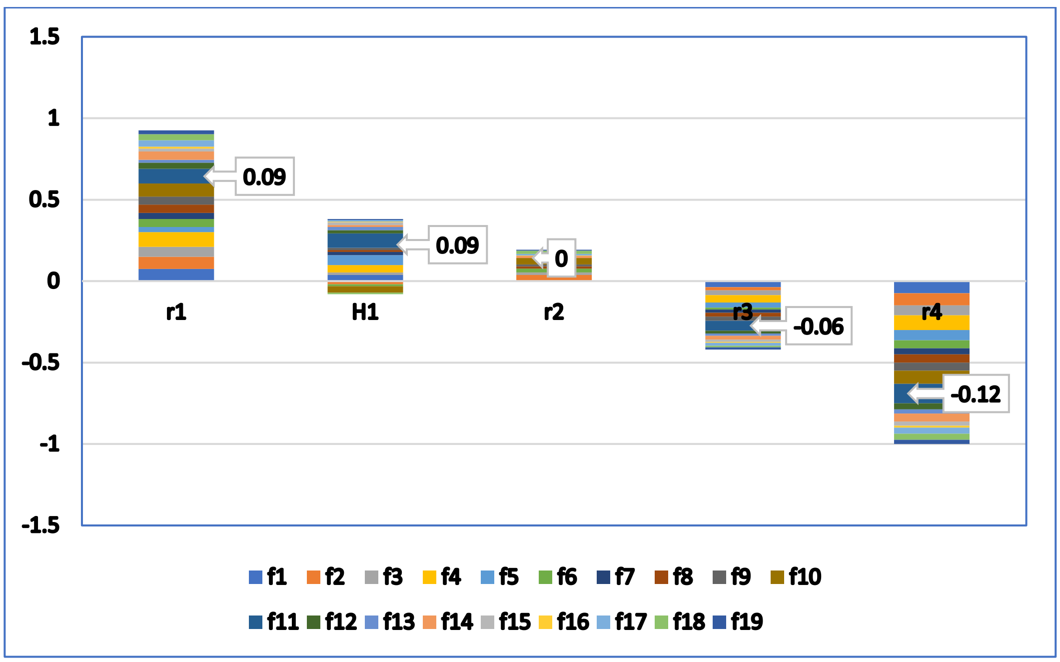

Figure 29. Assignment of high resilience for Homegarden H1.

For example, the value of the net flow of H1 (0.3006) is between net flows values corresponding to $r_1 = 0.9263$ and $r_2 = 0.1925$, which, in turn, delimit the high resilience category, for which H1 belongs to this category. Similarly, the belonging of the resilience category can be deduced from the rest of the orchards.

Another way of looking at the resulting category assignments is by graphing the net global flow values, with the advantage that we can enrich our understanding by visualizing the influence of the different criteria and respective weights. In Figures 29 and 30, we have plotted, as an example, the values of the net flow and the corresponding limit profiles of the orchard H1 and H12.

As already indicated in Table 21, the net flow value of H1 (0.3006) lies between r1 and r2, placing it in the high resilience category. The size of the rectangles expresses the contribution in the global flow value of the corresponding alternative (Figure 29).

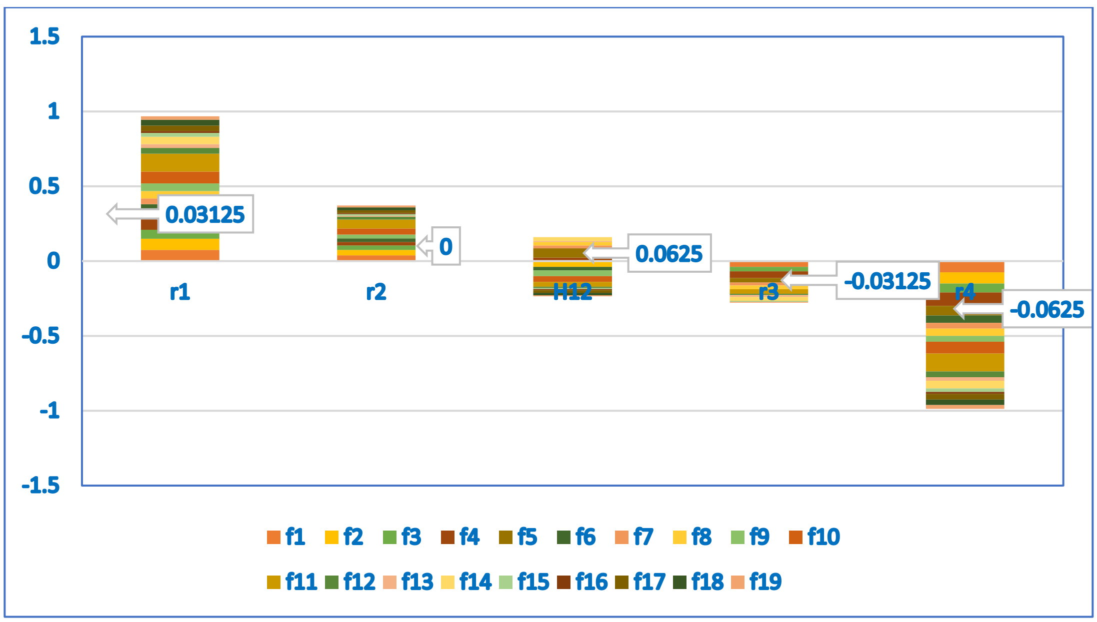

Figure 30. Assignment of medium resilience for Homegarden H12.

The strength of orchard H1 resilience is found in the performance of the criteria that contribute the most to the value of the net global flow: the criterion f11 (perception of saving for self-consumption) with 0.09, is the one with the most significant influence; it is followed by the criterion f5 (total number of individuals per m2- biological activity -edaphic macrofauna) with 0.0625 and f4 (number of use categories exploited by the family) with 0.045. Similarly, the weaknesses in resilience are found in the performance of criteria with the lowest contribution.

Similarly, the net flow value indicated in Table 21 of H12 (-0.0756) lies between the values of r2 and r3, placing it in the medium resilience category. The size of the rectangles expresses the contribution in the global flow value of the corresponding alternative (Figure 30).

The strength of orchard H12 resilience is found in the performance of the criteria that contribute the most to the value of the net global flow: the criterion f5 (total number of individuals per m^2 -biological activity-edaphic macrofauna) with 0.0625, is the one with the most significant influence; It is followed by the criterion f8 (local crops, varieties and breeds conserved) with 0.025, f14 (size or area of the property) 0.025, and f4 (number of use categories exploited by the family) with 0.0225. Similarly, the weaknesses in resilience are found in the performance of criteria with the lowest contribution.

4.5. Evaluation of sustainability based on resilience

As observed in Table 22, the H1, H2, H4, and H5 orchards belong to the high resilience category, while the rest belong to the medium resilience category. The high resilience of some orchards is mainly due to the increased dependence on products derived from these units to meet their food and other needs, which contributes to improving the economic resilience by saving cash.

Table 22. Level of sustainability based on HGs resilient category.

Category of resilience	**Level of sustainability**
High	Potentially sustainable
Medium	Average sustainable
Low	Potentially unsustainable

Besides, the high number of use categories exploited by the members of the households promotes agrobiodiversity in the study units. Furthermore, the ecological management and conservation practices and the greater involvement of the family members also contribute to ecological resilience and sustainability.

Assessing sustainability is very complex and requires a multidisciplinary analysis. This is because all the variables or criteria of each component are interrelated. Together, they contribute to determining the essential characteristics of HGs to maintain their structural and functional sustainability. However, the results of this study indicate that all the studied homegardens turn out to be composed of elements that both support and inhibit resilience, and therefore, they cannot be sustainable in 100%.

Thus, high resilient HGs are considered more sustainable (Table 22) within the range of thresholds established in this research. The other orchards, although present levels of medium degree resilience, this study finds as less sustainable because of the probability to descend from medium to low category of resilience in future, unless the desirable range of high resilience levels attained.

In other words, the medium resilient units face a high probability of descending to the low resilience category due to their negative performance in the components of organizational, management, and conservation capacity. To be specific, the acculturation process (i.e., the transgression of the cultural elements), migration, and the lack of appreciation for this inherited practice by the future generations in the near future could modify these units' structure and functions that influence the level of sustainability.

5. Conclusions

The conclusions that can be obtained from this work are as follows:

- Homegardens with high agrobiodiversity, management and conservation capacity, monetary gains, and organizational capacity contribute to increasing ecological, economic, and cultural resilience in the face of adverse challenges.
- Only about 33% of the study units belong to the high resilience category and therefore present a high degree of sustainability compared to other units with medium resilience. And, from the sustainability perspective, not

all units are 100% sustainable due to their negative performance in different criteria.

- The graphic presentation of the resilience index and FlowSort analysis results has made it possible to visualize and interpret the current degree of resilience of Totonac HGs, thereby its sustainability. Also, it facilitates the identification of systems limitations, potentialities, and opportunities.
- Thus, the more significant the transmission, conservation, and improvement of agrodiversity associated with homegardens and the degree of appreciation for it by current and future generations, the greater the integral resilience and sustainability of homegardens Totonacapan.

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Conflicts of Interest: The authors declare no conflict of interest.

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6. LIMITATIONS

The following limitations were found in the current study:

- This research on HGs has focused primarily on the local scale, i.e., concentrating on one community. Also, it assesses only the current degree of integral resilience of HGs, instead of evaluating the ex-ante and ex-post periods of resilience to specific shocks and stresses in the study area.
- The evaluation of the role of agrobiodiversity in this research primarily focuses on interspecific (variation between species) diversity of plant and animal components, and there is a lack of adequate data analysis on intraspecific (variation within species) diversity. To be specific, the concept of species is insufficient, and it is essential to consider the infraspecific variants (cultivar, subspecies, race, forms) to determine the status of agrobiodiversity in a zone. Also, cultural importance such as flavor, pungency, agronomic importance, or susceptibility to Phytopathological or environmental problems such as resistance to drought should be considered while inventorying species variants. Regarding fauna, very few domestic species, such as chicken, pig, or goat, were considered in the current research of the homegarden system. However, the role of wild or semi-domesticated species was not focused on in this study. Besides, this research did not analyze the importance of other living components associated with the agrobiodiversity of homegardens, such as fungi and microorganisms (bacteria, algae, lichens, insects, etc.). Therefore, as the potential use of many wild species within homegardens have only begun to be documented, further research from ethnoecological and ethnobotanical approaches are required to identify the plant and animal resources to implement a win-win strategy in tackling both livelihood challenges as well as sustainable development constraints
- Regarding the structural diversity, this research did not evaluate or analyze the mechanisms of interactions or the flow of energy below and above the

ground of the homegarden agroecosystems. Also, the functional structure of homegardens is not given enough focus to understand well (Wiehle *et al*., 2014). Therefore, more research should focus the functional dynamics of homegardens based on their structural diversity to understand the complexity involved in it to improve the mechanisms of these systems in the near future.

- Regarding functional diversity, this research did not provide quantitative data regarding the functional dynamics of this complex agroforestry system. Also, this research did not consider evaluating the functional equivalence or redundancy (i.e., multiple species representing various taxonomic groups can share similar, if not identical, roles in ecosystem functionality, for example, nitrogen fixers) suggested by Salmerón, Geada, and Fagilde Espinoza (2017).
- As homegarden is a dynamic system with constant changes, the estimated data of species richness in this research corresponds to the period of data collection. Also, the sample size of this study is very limited, and therefore, the status of agrodiversity could not possibly represent the whole region.
- Besides, as limited plant specimens were collected to identify their taxonomical characteristics, identifying intraspecific species was impossible. Also, this study did not analyze the correlated factors that influence plant or species diversity in homegardens. Thus, although the family members' personal preferences are critical in determining the floristic composition of homegardens, a broad range of other variables (related to ecological conditions, cultural demands, and socio-economic context) also influence the crop diversity of homegardens.
- The study area's biophysical, organizational, and management diversity were evaluated in this research using different qualitative methods such as literature review, semi-structured interview, participatory and direct observations, etcetera. The limitation in the evaluation of these three components is that the collected information might be subjective.

7. GENERAL CONCLUSIONS

The conclusions that can be obtained from this work are as follows:

One of the main contributions of this work is the identification of the fundamental role of agrodiversity components (agrobiodiversity, management, and conservation capacity, monetary gains, and organizational capacity) and its indicators to maintain the structure and function, i.e., the integral (ecological, economic, and sociocultural) resilience of homegardens.

The second contribution is designing a flexible methodological framework to assess the current degree of integral resilience of homegardens. Thus, the developed methodology is a complementary approach to evaluating sustainability based on resilience. It could be replicated or adapted to different agroecosystems under various biophysical, economic, and sociocultural conditions.

The third contribution is assigning the limiting profiles (i.e., the baseline value determination or the process of threshold) for each variable to determine the categories of a high, medium, and low resilience of homegardens. Thus, the thresholds could guide decision-makers to plan for desirable scenarios and identify interventions to modify undesirable current trends in policy making of homegarden promotion. In other words, it allows identifying the weakness and potentials of the system.

Finally, considering the hypothesis of the problem, this study concludes that: the more significant the transmission of the biocultural heritage associated with agrodiversity of homegardens and the degree of attachment to it by the current and future generations, the greater the integral resilience of homegarden agroecosystems, and consequently, the sustainability evidenced in them.

8. RECOMMENDATIONS

Totonac homegardens in the study area, in general, represent the multifunctional agroecosystems that meet the internal needs of the family and provide other ecological functions (such as nutrient cycling, photosynthetic route enhancement, resistance to plant diseases) and services (such as food, recreation habitat) which are fundamental to enhance human well-being.

Besides, HGs provide a way to achieve food sovereignty by protecting the legal rights of local people regarding the use and equitable sharing of natural resources. And, they act as a safety net in providing alternative livelihood sources to the family during crisis periods such as conflicts, natural hazards, the pandemic of covid 19. Also, they play an essential role in conserving the biocultural knowledge of the native people. Thus, its scope to contribute to sustainable rural development is higher than monocultures or other agricultural practices.

However, from experience in the development of this work, the following recommendations are made to enhance the integral resilience of homegardens in the study area to confront emerging challenges:

- To enhance the ecological resilience of the homegardens, it is highly recommended that sustainable rural development programs promote traditional HGs as a biocultural heritage either by raising awareness or by offering payment for environmental services to conserve and intensify the species, structural and functional diversity within HGs. Also, building the capacity of the household members to improve their knowledge regarding agroecological management practices and conservation strategies (both *in situ* and *ex situ*).
- To improve the economic resilience of the homegardens, it is necessary to strengthen them by adding market value to the HG products to generate income and savings. Also, integrate other components in the productive processes of these units to make them economically profitable and more sustainable while respecting their socio-cultural elements. Besides, it is

essential to encourage the production and marketing on a larger scale of both traditional and non-traditional local products in HGs.

- To increase socio-cultural resilience, it is essential to conduct frequent training or workshops to improve the transfer of local biocultural knowledge to young generations by exchanging information within and between different cultural or ethnic groups and developing local tools to protect traditional knowledge agroecosystems such as homegardens. For instance, the collection and registration of information relevant to native plant and animal resources, traditional food, calendar of land-use activities, folklore, customs, and traditions in both native and Spanish language will be helpful for future use and empowerment of farmers. This indeed promotes solid social networks of reciprocity and seed or knowledge exchange. Above all, it is fundamental to create more livelihood opportunities at a local scale to avoid the migration of youngsters.
- Also, it is recommended to conduct participatory, interdisciplinary, and transdisciplinary research to evaluate the whole dynamics of homegardens where both ecological and cultural aspects equally play an important role. Besides, it will help build the resilience of these systems by designing and implementing policies based on their strengths and weaknesses.
- In addition, it is recommended to analyze the potential role of HGs to capture and store carbon and thereby its contribution to mitigate and adapt to climate change. For this, we could propose a hypothesis to consider in future research that homegardens with a higher potential to mitigate and adapt to climate change are also those with a higher degree of resilience.
- Many youngsters prefer to migrate in search of alternative options for their livelihood instead of continuing their traditional land-use practice due to the increasing economic pressure or needs and changes in their lifestyle. Thus, the reassessment or follow-up after two, five, and ten years from the current period is recommended to analyze this trend and design policies to enhance the sustainability based on HGs resilience in the study area.

Appendix 1. Plant species are found in the Totonac homegardens of Santiago Ecatlan, State of Puebla, Mexico.

N°	Family	Scientific name	Common name	Spanish & (Totonac) name	Habit	Use category[1]	Parts used[3]	Managed form[2]	Strata	Status
1	Acanthaceae	*Pachystachys lutea* Nees	Golden shrimp	Camarón amarillo/ Cucuaracha	Shrub	Or	F	C	0-1 m	Introduced
2	Adoxaceae	*Sambucus nigra* L.	Mexican elderberry	Sauco (Tokgxihua)	Tree	Me, Ce	L, F	C	>5 m	Introduced
3	Amaranthaceae	*Amaranthus hybridus* L.	Red amaranth/ Pigweed	Quintonil (Kgalhtunit)	Herb	Fd, Or, Me	L, G, F	C	0-1 m	Native
4	Amaranthaceae	*Celosia argentea* L.	Plumed cockscomb	Cresta de gallo/ Mano de león (Puyuxánat)	Herb	Or	P, F	C	0-1 m	Introduced
5	Amaranthaceae	*Dysphania ambrosioides* L.	Mexican tea	Epazote (Lhkgéjni)	Herb	Sp, Me	L	C	0-1 m	Native
6	Amaranthaceae	*Gomphrena globose* L.	Globe amaranth	Sempiterna (Pasmaxanat)	Herb	Or, Ce	P, L	C	0-1 m	Introduced
7	Amaryllidaceae	*Allium schoenoprasum* L.	Onion grass/ Chives	Cebollina (Akgatsasna)	Herb	Sp, Me	L	C	0-1 m	Introduced
8	Anacardiaceae	*Spondias mombin* L.	Mombin/Hog plum	Jobo (Xipa´a)	Tree	Fd, Su	Fr, P	F	>5 m	Native
9	Anacardiaceae	*Mangifera indica* L.	Mango	Mango	Tree	Fd, Su	Fr, P	C	>5 m	Introduced
10	Apiaceae	*Eryngium foetidum* L.	False coriander	Cilantro extranjero (Kulantru)	Herb	Sp, Me	L	C	0-1 m	Native
11	Apocynaceae	*Allamanda cathartica* L.	Golden allamanda	Copa de Oro	Shrub	Or	P, F	C	1-3 m	Introduced
12	Apocynaceae	*Plumeria rubra* L.	Red paucipan	Flor de Mayo/ Cacalosúchil (Kgaxtaxánatl)	Tree	Or, Su	F, P	F	>5 m	Native
13	Araceae	*Anthurium scherzerianum* Schott	Flamingo flower	Anturio	Herb	Or	F, P	C	0-1 m	Introduced
14	Araceae	*Spathiphyllum wallisii* Regel	Peace lily/ Spathe flower	Cuna de moisés	Herb	Or	F, P	C	0-1 m	Introduced
15	Araceae	*Xanthosoma sagittifolium* (L.) Schott	Arrow leaf elephant ear	Mafafa morada/cinco quelites (Paxnicaca /Akgpixix)	Herb	Fd, Me	L, S, B	F	0-1 m	Introduced

16	Araceae	*Zantedeschia aethiopica* (L.) Spreng.	Calla Lily	Alcatraz	Herb	Or	P, F	C	0-1 m	Introduced
17	Arecaceae	*Chamaedorea elegans* Mart.	Parlour palm	Tepehilote/Palmilla (Lilhtampa)	Other	Or	P, L	F	1-3 m	Endemic
18	Arecaceae	*Chamaedorea tepejilote* Liebm. Ex Mart.	Palm/ Pacaya	Tepejilote rojo (Lilhtampa)	Other	Or, Ha	P, L	F	1-3 m	Endemic
19	Begoniaceae	*Begonia sp.*	Starleaf begonia	Xocoyol/Begonia (Xcutni)	Herb	Fd, Or	L, P	F	0-1 m	Introduced
20	Begoniaceae	*Begonia heracleifolia* Cham & Schltdl.	Starleaf begonia	Xocoyol agrio (Xcutni/Xcuta)	Herb	Fd, Or	L, P	F	0-1 m	Introduced
21	Bignoniaceae	*Crescentia cujete* L.	Calabash/ Gourd tree	Jícara (Kiwi poke)	Tree	Ha, Or	Fr, P	C	>5 m	Native
22	Burseraceae	*Bursera simaruba* (L.) Sarg.	Turpentine/ Gum tree	Chaca/Palo mulato (Túzun)	Tree	Wo, Su	W, F	F	>5 m	Introduced
23	Cactaceae	*Opuntia spp.*	Cactus	Cactus	Other	Or	P	F	0-1 m	Native
24	Caricaceae	*Carica papaya* L.	Papaya	Papaya (Tutunchichí)	Shrub	Fd, Me	Fr, L	C	1-3 m	Native
25	Compositae	*Tagetes erecta* L.	Mexican Marigold	Flor de muerto (Cempoalxochitl /Kgalhpuxam)	Herb	Or, Ce	P, F	C	0-1 m	Native
26	Compositae	*Dahlia sp.*	Red dahlia	Dalia (Xanat)	Shrub	Or	P, F	C	1-3 m	Native
27	Compositae	*Verbesina persicifolia* (DC.) Bip. Ex Hemsl.	Bull grass	Huichín (Huixina)	Herb	Me, Fo	L	P	0-1 m	Native
28	Compositae	*Porophyllum ruderale* (Jacq.) Cass.	Pore leaf	Papaloquelite (Pucsnancaca)	Herb	Sp, Me	L	C	0-1 m	Native
29	Costaceae	*Costus spicatus* (Jacq.) Swartz.	Spiked spiral flag ginger	Caña de jabalí (Kxakatpaxni)	Herb	Me, Or	S, P	P	1-3 m	Introduced
30	Cucurbitaceae	*Sicana odorifera* (Vell.) Naudin.	Sikana Cassabanana	Calabaza melon (Nipxi)	Herb	Fd, Fo	Fr	C	1-3 m	Introduced
31	Cucurbitaceae	*Lagenaria siceraria* (Molina) Standl.	Bottle gourd	Calabaza tipo cuchara/ Guaje (Xical)	Other	Fd, Ha	L, F, Fr	C	1-3 m	Introduced
32	Cucurbitaceae	*Sechium edule* (Jacq.) Sw.	Squash	Chayote espinosa (Malkgtukún)	Other	Fd, Me	L, Fr, Se	C	1-3 m	Native
33	Cucurbitaceae	*Cucurbita spp.*	Pumpkin	Calabaza (Nipxi)	Other	Fd, Me	L, S, Fr	C	1-3 m	Native

34	Dioscoreaceae	*Dioscorea bulbifera* L.	Aerial yam/ Bitter yam	Papa voladora/ Papa de monte (Shunapapas)	Other	Fd, Me	B, L	F	1-3 m	Introduced
35	Ebenaceae	*Diospyros digyna* Jacq.	Black sapote	Zapote negro (Sawalhkg)	Tree	Fd, Wo	Fr, T	C	3-5 m	Native
36	Equisetaceae	*Equisetum arvense* L.	Horsetail	Cola de caballo	Herb	Me	L	P	0-1 m	Introduced
37	Euphorbiaceae	*Manihot esculenta* Crantz.	Cassava/Tapioca	Yuca (Kogxkiwi)	Shrub	Fd, Or	B, P	C	1-3 m	Introduced
38	Euphorbiaceae	*Codiaeum variegatum* (L). Rumph, ex. Juss.	Garden croton	Crotón variegado	Shrub	Or, Su	P	C	1-3 m	Introduced
39	Euphorbiaceae	*Croton draco* Schltdl.	Sangre draco	Sangre de grado (Puklhnankiwi)	Tree	Wo, Su, Me	T, La	F	>5 m	Native
40	Euphorbiaceae	*Euphorbia pulcherrima* Willd. Ex Klotzsch.	Christmas flower	Nochebuena (Palkgtuxanatl)	Shrub	Or, Ce	P	C	1-3 m	Native
41	Euphorbiaceae	*Jatropha curcas* L.	Physic nut	Piñon mexicano (Chuta/Puxni)	Shrub	Fo, Or, Me	Se, P	C	1-3 m	Native
42	Euphorbiaceae	*Ricinus communis* L.	Castor bean	Higuerilla	Shrub	Or, Fu	P, Se	C	1-3 m	Introduced
43	Heliconiaceae	*Heliconia sp.*	Lobster claws	Platanillo (Liwapan)	Herb	Or, Ut	P, L	F	0-1 m	Introduced
44	Iridaceae	*Gladiolus sp.*	Corn flag/ Sword lily	Gladiola	Herb	Or	P, F	C	0-1 m	Introduced
45	Lamiaceae	*Mentha spicata* L.	Garden mint	Yerbabuena (Alhmuwina)	Herb	Sp, Me, Be	L	C	0-1 m	Introduced
46	Lamiaceae	*Ocimum basilicum* L.	Basil	Albahaca (Xpasimakatoro)	Herb	Ce, Sp	L	C	0-1 m	Introduced
47	Lamiaceae	*Scutellaria guatemalensis* Leonard.	Skullcaps/ Mirtos de escudo	Maltantzin (Paculimatawan)	Herb	Me, Sp	L	P	0-1 m	Introduced
48	Lamiaceae	*Thymus vulgaris* L.	Thyme	Tomillo	Herb	Sp, Me	L	C	0-1 m	Introduced
49	Lamiaceae	*Origanum vulgare* L.	Oregano/ Pot marjoram	Orégano	Herb	Sp, Me	L	C	0-1 m	Introduced
50	Lauraceae	*Persea americana* Mill.	Avocado	Aguacate (Kukuta)	Tree	Fd, Me	Fr, L, S	C	>5 m	Native
51	Leguminosae	*Arachis hypogaea* L.	Peanut	Cacahuate (Kakawati)	Herb	Fd, Fo	Se, L	C	0-1 m	Introduced
52	Leguminosae	*Gliricidia sepium* (Jacq.) Walp.	Mexican lilac/ Forest lilac	Cocuite/Cuacuite (Pupútkiwi)	Tree	Fu, Su, Fo	Tr, Br, L	F	>5 m	Native

53	Leguminosae	*Inga jinicuil* Schltdl.	Ice cream bean	Jinicuil/Talaxca (Talaxka)	Tree	Fd, Fu	Fr, Tr	F	>5 m	Native
54	Leguminosae	*Phaseolus vulgaris* L.	Common bean/ Garden bean	Frijol gordo (Laktlankástapu/ Stapu)	Herb	Fd, Fo	L, Fr, Se	C	0-1 m	Native
55	Leguminosae	*Inga vera* Willd.	Guaba/Ice cream bean	Chalahuite (Kalaman)	Tree	Fd, Su	Fr, P	F	>5 m	Native
56	Leguminosae	*Leucaena leucocephala*	Leucaena	Guaje/Huaxi (Liliakg)	Tree	Fd, Fo	L, Se	F	>5 m	Native
57	Liliaceae	*Lilium candidum* L.	Madonna lily	Flor de San Jose/ Azucena	Herb	Or	P, F	C	0-1 m	Introduced
58	Malvaceae	*Heliocarpus appendiculatus* Turcz	Sun-fruit/Majagua	Jonote (Panamak xunik)	Tree	Su, Me, Fi	P, Tb	F	>5 m	Introduced
59	Malvaceae	*Hibiscus rosa-sinensis* L.	Chinese Hibiscus/ Chinese rose	Tulipán	Shrub	Or, Me	F	C	1-3 m	Introduced
60	Malvaceae	*Abelmoschus manihot* (L.) Medik.	Sunset musk mallow	Santa Elena	Shrub	Or, Me	P, Se	P	0-1 m	Introduced
61	Malpighiaceae	*Byrsonima crassifolia* (L.) Kunth	Hogberry/ Nance	Nispero	Tree	Fd, Su	Fr	F	>5 m	Native
62	Meliaceae	*Cedrela odorata* L.	Spanish cedar	Cedro (Pukgsnan kiwi)	Tree	Wo, Su	Tr, P	C	>5 m	Native
63	Musaceae	*Musa sp.*	Banana	Plátano (Seakgna)	Herb	Fd, Ut	F, L	C	3-5 m	Introduced
64	Myrtaceae	*Pimenta dioica* L. Merr.	Allspice/ Jamaica pepper	Pimienta (O´kum)	Tree	Sp, Me	L, Fr, Se	C	>5 m	Native
65	Myrtaceae	*Psidium guajava* L.	Guava	Guayaba (Asihuit)	Tree	Fd, Me	Fr, L	C	3-5 m	Native
66	Nyctaginaceae	*Bougainvillea glabra* Choisy.	Buganvilla/ Paper flower	Bugambilia (Xpupukut xanat)	Other	Or, Me	P, L	C	1-3 m	Introduced
67	Nyctaginaceae	*Mirabilis jalapa* L.	Miracle flower of Peru	Flor de maravilla	Herb	Or	P, F	C	0-1 m	Introduced
68	Orchidaceae	*Vanilla planifolia* Jacks. Ex Andrews.	Vanilla	Vainilla (Zumi xánat)	Other	Sp, Or	Sh, P	C	3-5 m	Endemic
69	Passifloraceae	*Passiflora edulis* Sims.	Common passion fruit	Maracuyá (Puxulukut)	Other	Fd, Or	Fr, P	C	3-5 m	Introduced
70	Piperaceae	*Peperomia glabela* var. *Nigropunctata* (Mig.) Dahlst.	Culantro/ coriander	Tequelite (Juksasan)	Herb	Fd, Me	L	F	0-1 m	Introduced

71	Piperaceae	*Piper auritum* Kunth.	Sacred leaf	Hierba Santa/ Omequelite (Jinan)	Herb	Ut, Me	L	F	1-3 m	Native
72	Poaceae	*Saccharum officinarum* L.	Sugarcane	Caña de azucar (Chankat)	Herb	Fd, Fo	St, L	C	1-3 m	Introduced
73	Poaceae	*Bambusa vulgaris* Schrad. ex J.C. Wendl.	Bamboo	Bambú (Matlug)	Herb	Wo, Su	S	C	>5 m	Introduced
74	Poaceae	*Coix lacryma-jobi* L.	Indian beads/ Job's tears	Lágrimas de san pedro (Saqut tapixnu)	Herb	Ha, Or	Se, L, S	F	1-3 m	Introduced
75	Poaceae	*Zea mays* L.	Corn/Maize	Maíz (Cuxi)	Herb	Fd, Ut	G, L	C	1-3 m	Native
76	Poaceae	*Cymbopogon citratus* (DC.) Stapf	Lemon grass	Zacate/ Té limón	Herb	Be, Me	L	F	0-1 m	Introduced
77	Portulacaceae	*Portulaca grandiflora* Hook.	Rose Moss	Amor de un rato (Skúptama)	Herb	Or	P	F	0-1 m	Introduced
78	Rosaceae	*Prunus persica* (L.) Batsch	Peach	Durazno	Tree	Fd, Or, Su	Fr, P	C	>5 m	Introduced
79	Rosaceae	*Prunus domestica* L.	Common plum	Ciruelillo	Tree	Fd, Or	Fr, P	C	>5 m	Introduced
80	Rosaceae	*Prunus serotina* Ehrh.	Wild black cherry	Capulín (Akgtalawat)	Tree	Fd, Su	Fr, P	C	>5 m	Native
81	Rosaceae	*Rosa sp.* L.	Rose	Rosa	Shrub	Or	F, P	C	1-3 m	Introduced
82	Rosaceae	*Rubus ulmifolius* Schott.	Blackberry/ Bramble	Zarzamora	Shrub	Fd, Su	Fr	C	0-1 m	Introduced
83	Rubiaceae	*Coffea arabica* L.	Coffee	Café (Kapej)	Shrub	Be, Ha	Fr	C	1-3 m	Introduced
84	Rubiaceae	*Hamelia patens* Jacq.	Fire bush/ Scarlet bush	Tochomitillo (Makglhtuntunkgch)	Shrub	Me, Or	L, P	F	1-3 m	Native
85	Rubiaceae	*Gardenia jasminoides* J. Ellis	Gardenia/ Cape jasmin	Gardenia	Shrub	Or	F, P	C	1-3 m	Introduced
86	Rubiaceae	*Morinda citrifolia* L.	Indian mulberry	Noni	Tree	Fd, Su	Fr	C	>5 m	Introduced
87	Rutaceae	*Ruta graveolens* L.	Bitter herb/ Garden herb/Rue	Ruda	Shrub	Sp, Me	L	C	0-1 m	Introduced
88	Rutaceae	*Citrus reticulata* Blanco.	Mandarine orange	Mandarina (Mandarina laxux)	Tree	Fd, Me, Be	Fr, L	C	3-5 m	Introduced
89	Rutaceae	*Citrus sinensis* (L.) Osbeck	Sweet orange/ Valencia orange	Naranja (Laxux)	Tree	Fd, Me, Be	Fr, L	C	3-5 m	Introduced

90	Rutaceae	*Citrus aurantifolia* (Christm.) Swingle	Lemon	Limón persa (Xukut)	Tree	Fd, Me, Be	Fr, L	C	1-3 m	Introduced
91	Rutaceae	*Murraya paniculate* (L.) Jack	Orange jasmine	Limonaria	Tree	Or	P	C	1-3 m	Introduced
92	Sapotaceae	*Pouteria sapota* (Jacq.) H.E. Moore & Stearn	Mamey sapote	Mamey (Jaâka)	Tree	Fd, Or	Fr, P	C	>5 m	Native
93	Solanaceae	*Solanum nigrescens* M. Martens & Galeotti	Divine nightshade	Hierbamora (Mustulut)	Herb	Fd, Me	Fr, L	C	0-1 m	Native
94	Solanaceae	*Capsicum annuum* L. var. *Jalapeño*	Bell pepper/ Chillies	Chile grande (Pin)	Shrub	Sp, Me	Fr	C	0-1 m	Native
95	Solanaceae	*Capsicum annuum* var. *glabriusculum* (Dunal) Heiser & Pickersgill	Indian pepper/ Cayenne pepper/ Chile tepin	Chiltepín (Akgsú-pin)	Shrub	Sp, Me	Fr	C	0-1 m	Native
96	Solanaceae	*Solanum lycopersicum* L.	Tomato	Jitomate (Pakglhcha)	Herb	Fd, Me	Fr, L	C	0-1 m	Native
97	Solanaceae	*Physalis ixocarpa* Brot. Ex Hornem.	Mexican-ground cherry	Tomate de cascara/ Tomatillo	Herb	Fd, Me	Fr, L	C	0-1 m	Native
98	Solanaceae	*Nicotiana tabacum* L.	Tabacco	Tabacco (Axcut)	Herb	Or, Me	L	C	0-1 m	Introduced
99	Xanthorrhoeaceae	*Aloe vera* (L.) Burm. f.	Aloe	Sábila (Chuyún)	Other	Or, Me	P, L, La	F	0-1 m	Introduced
100	Zingiberaceae	*Renealmia alpinia* (Rottb.) Maas	Garden ginger	Frutilla (Xquijit)	Herb	Fd, Ut	Fr, L	F	1-3 m	Introduced
101	Zingiberaceae	*Alpinia purpurata* (Vieill.) K. Schum.	Red ginger	Hawaiana	Herb	Or, Ut	P, F, L	F	1-3 m	Introduced

[1]**Use category:** Fd-Food; Sp-Spice; Be-Beverages; Me-Medicinal; Fi-Fiber; Ut-utensil; Fu-Fuel; Ha-Handcrafts; Wo-Wood; Fo-Fodder; Ce-Ceremonial; Or-Ornamental; Su-Sustenance (refuge, recreation, shade, habitat for wild animals, supporting material as a tutor, etc.).
[2]**Managed form:** P-Protected; F-Fomented; C-Cultivated.
[3]**Parts used:** Se-Seed; S-Stem; Tr-Trunk; Tb-Tree bark; Br-Branches; L-Leaves; F-Flower; Fr-Fruit; B-Bulb; G-Grain; P-Whole plant; Sh-Sheath; St-Stalk or cane; La-Latex.

Appendix 2. Matrix of weights, criteria, and scope for the component of agrobiodiversity.

Attribute: Ecological resilience				
Component: Agrobiodiversity (ABD) - **w_i**** - 0.25				
Indicators (Ind)	**q_{ij}*****	**Variables**	**Criteria**	**Score**
Species diversity[1, 2, 4, 6*]	0.15	Plant resources, i.e., the number of plant species found in HGs [f1] ****	>100 species	5
			76-100 species	4
			51-75 species	3
			25-50 species	2
			<25 species	1
	0.15	Animal resources (pig, chicken, turkey, duck, horse, donkey) found in HGs [f2]	>5 species	5
			4 species	4
			3 species	3
			2 species	2
			1 species	1
Structural diversity [1, 2, 4*]	0.10	Number of strata (vertical organization of plant species) [f20].	>5 strata	5
			4 strata	4
			3 strata	3
			2 strata	2
			1 strata	1
	0.10	The number of life forms (tree, herb, shrub, vine, and others). [f21]	>5 forms	5
			4 forms	4
			3 forms	3
			2 forms	2
			1 form	1
	0.10	The number of management zones (fruit trees, ornamental plants, herbaceous crops, multi-purpose trees, animal sheds, sheds for seed and fuelwood, residence area). [f3]	All 7 zones	5
			6 zones	4
			5 zones	3
			3-4 zones	2
			1-2 zones	1
Functional diversity [1, 2, 3, 4*]	0.20	Number of use categories exploited by the family [f4]	12-13 uses	5
			9-11 uses	4
			6-8 uses	3
			4-5 uses	2
			1-3 uses	1
	0.20	Use and availability of food in HG (e.g., cereals, vegetables, fruits, nuts, wild plants, mushroom, and animals in a year) [f22]	All year	5
			10-11 months	4
			7-9 months	3
			4-6 months	2
			1-3 months	1
			Organic & inorganic	3
			Inorganic only	2
			Mechanical energy	1

*Methods employed for measurement of each indicator: 1) Semi-structured interview; 2) Participatory and direct observation; 3) Surveys; 4) Ethnobotanical exploration; 5) Edaphic macrofauna evaluation; 6) Diversity index analysis; **w_i = weight of component i; ***q_{ij} = weight of variable j of component I; ****short abbreviations of each variable.

Appendix 3. Matrix of weights, criteria, and scores for the component of management and conservation capacity.

Attribute: Ecological resilience				
Component: Management and conservation capacity (MCC) - **w_i**** - 0.25				
Indicators (Ind)	**q_{ij}*****	**Variables[f]******	**Criteria**	**Score**
Soil quality [5*]	0.15	Biological activity of edaphic macrofauna (total number of individuals/m^2) [f5]	>900 individual/m^2	5
			450-900	4
			400-450	3

			300-400	2
			<300 individuals/m^2	1
Water availability [2*]	0.10	Frequency of water availability [f23]	Always (365 days)	5
			Often (280-364 days)	4
			Sometimes (181-279)	3
			Rarely (1-180 days)	2
			Never	1
	0.05	Distance to water bodies i.e., access [f24]	Very near (0-50 meter)	5
			Near (51-200 meter)	4
			Neutral (201-500 meter)	3
			Far (501-1000 meter)	2
			Very far (>1000 meter)	1
Pest management [2*]	0.05	Pest incidence observed in plants of the gardens (number of plants affected) [f25]	No pest	5
			<4 plants	4
			5 plants	3
			6-7 plants	2
			>7 plants	1
	0.05	Disease observed in animals of the gardens (percentage of animals) [f26]	No disease	5
			<25%	4
			25-50%	3
			50-75%	2
			>75%	1
Labor activities [1, 2, 3*]	0.10	Frequency of garden management activity (number of days/week) [f6]	>5 days/week	5
			4-5 days/week	4
			3 days/week	3
			2 days/week	2
			Once a week	1
	0.10	Frequency of animal management activity [f27]	>5 days/week	5
			4-5 days/week	4
			3 days/week	3
			2 days/week	2
			Once a week	1
Daily action area [1, 2*]	0.10	Number of places (milpa, natural vegetation, market, family, social gathering places) within and between communities connected (access and exchange resources) [f7]	All 5	5
			4 of 5	4
			3 of 5	3
			2 of 5	2
			1 of 5	1
Conservation practices [1, 2, 3*]	0.05	Type of energy (use of manual instruments vs. machinery and organic fertilizers vs. agrochemicals) [f28]	Human energy & organic	5
			Organic only	4
			Organic & inorganic	3
			Inorganic only	2
			Mechanical energy	1
	0.05	Agrochemical used (i.e., the intensity of contamination) [f29]	Very low	5
			Low	4
			Medium	3
			High	2
			Very	1
	0.10	Local crops, varieties, and breeds conserved [f8]	>9 plants	5
			7-8 plants	4
			5-6 plants	3
			3-4 plants	2
			1-2 plants	1
	0.10	Local crops, varieties, and breeds information documented [f9]	Always	5
			Often	4
			Sometimes	3
			Rarely	2
			Very rarely	1

*Methods employed for measurement of each indicator: 1) Semi-structured interview; 2) Participatory and direct observation; 3) Surveys; 4) Ethnobotanical exploration; 5) Edaphic macrofauna evaluation; 6) Diversity index analysis; **w_i = weight of component i; ***q_{ij} = weight of variable j of component I; ****short abbreviations of each variable.

Appendix 4. Matrix of weights, criteria, and score for the component of monetary gains and organizational capacity.

Attribute: Economic resilience				
Component: Monetary gains (MG) - $\mathbf{w_i^{**}}$ **-** 0.20				
Indicators (Ind)	$\mathbf{q_{ij}^{***}}$	**Variables (f)**	**Criteria**	**Score**
Level of income [1, 2, 3*]	0.40	Perception of income from the sale of HG products [f10]. (These incomes were evaluated in pesos per week compared with the percentage of approximate income from the main occupation in each unit).	Very high (80-100%)	5
			High (60-80%)	4
			Medium (40-60%)	3
			Low (20-40%)	2
			Very low (0-20%)	1
Level of savings [1, 2,3*]	0.60	Perception of savings for self-consumption (use of garden products per year) [f11]. (These savings were evaluated in pesos per week compared with the percentage of approximate cash spent to acquire food in each unit).	Very high (80-100%)	5
			High (60-80%)	4
			Medium (40-60%)	3
			Low (20-40%)	2
			Very low (0-20%)	1
Attribute: Sociocultural resilience				
Component: Organizational (OC) - $\mathbf{w_i^{**}}$ **-** 0.25				
Indicators (Ind)	$\mathbf{q_{ij}^{***}}$	**Variables**	**Criteria**	**Score**
Family participation [1, 2, 3*]	0.15	Family participation in management activities of HG [f12]	All members	5
			Women and children	4
			Rarely children	3
			Adults only	2
			Paid labor	1
	0.05	Family participation in community activities and religious festivals [f13]	Always	5
			Often	4
			Sometimes	3
			Rarely	2
			Very rarely	1
Access to public services [2*]	0.05	Access to drinking water, light, health services, education, and telecommunications [f30]	All 5	5
			4 of 5	4
			3 of 5	3
			2 of 5	2
			1 of 5	1
Land tenure [2*]	0.10	Land ownership [f31]	Owner with land title	5
			Owner with title from peasant organization	4
			Collective property	3
			Renter	2
			None	1
	0.15	Size or area of the property [f14]	1000-3000 m^2	5
			501-1000 m^2	4
			201-500 m^2	3
			101-200 m^2	2
			1-100 m^2	1
Transmission of local biocultural knowledge [1, 2, 3*]	0.10	The practice of native language [f15]	All members	5
			Children speak	4
			Children understand	3
			Adults only	2
			None	1
	0.05	Use of native dress, the practice of traditional dance or song, and participation in religious activities [f16]	>3 activities	5
			All 3	4
			2 of 3	3
			1 of 3	2
			None	1
	0.10	Degree of knowledge of the third generation about traditional food and the resources used [f17]	Excellent	5
			Good	4
			Fair	3
			Poor	2
			Very poor	1
	0.10		Excellent	5

		Knowledge of land-use practices and associated biological resources and cosmology transmitted from second to successive generations [f18]	Good	4
			Fair	3
			Poor	2
			Very poor	1
	0.10	Number of generations continue practicing HG for subsistence and income [f19]	>4	5
			4	4
			3	3
			2	2
			1	1
	0.05	Knowledge about plant use (Number of forms of preparation or utilization of plants known) [f32]	>20 forms of use	5
			16-20 forms-use	4
			11-15 forms-use	3
			5-10 forms-use	2
			1-4 forms-use	1

*Methods employed for measurement of each indicator: 1) Semi-structured interview; 2) Participatory and direct observation; 3) Surveys; 4) Ethnobotanical exploration; 5) Edaphic macrofauna evaluation; 6) Diversity index analysis; **w_i = weight of component i; ***q_{ij} = weight of variable j of component I; ****short abbreviations of each variable.

Appendix 5. The components of the ecological environment (in the causal order) of study area.

Name of the community		Santiago Ecatlan or Ecatlan
Municipality		Jonotla
State		Puebla
Culture		Totonac
Priority Land Regions (RTP)		105-Cuetzalan
Geological	Geological period (emergence in the Cenozoic era 66 million years ago)	Cretaceous (81%)
		Jurassic (7%)
		Neogene (6%)
		Quaternary (3%)
	Type of rock	Extrusive igneous (6% of volcanic ash)
		Sedimentary (45%of limestone, 35% of shale y 7% de shale limestone)
		Aluvial soil (4%)
Geographic	Physiography	Eastern Sierra Madre (74%) and northern gulf coastal plain (26%).
	Topoform systems	Steep high Sierra (70%); typical hillock (26%) y low Sierra (4%).
	Geographical coordinates	20 ° 00 'and 20 ° 10' north latitude; meridians 97° 27' and 97° 36' west longitude
	Elevation	The communities of Jonotla municipality are situated in a range of 100-1100 m. a. s. l.
		Homegardens in the community of Santiago Ecatlán: 550-680 m. a. s. l.
Climate	Type of climate	A (C) (w) i´ g
	Climate in words	A warm climate that tends to be temperate, with a rainy season in summer, little oscillation, and an annual march of the Ganges type temperature (double maximum irradiance)
	Mean annual temperature	26.4° C
	Mean annual precipitation	4100 mm
	Winter precipitation	495 mm (11.19%)
	Thermic oscillation	9.2°C
Edaphic	Type of soil	Leptosol (47.7%); Regosol (36.88%); Phaeozem (7.94%); Andosol (5.09%)
Vegetation	Type of vegetation	Mesophilic mountain forests and High perennial forest
	Soil use	Agriculture (60%)
		Pasture land (25%)
		Jungle (6%)
		Forest (6%)
		Urban zone (3%)
Animal	Type of domestic animals	Chickens, horses, parrots, pets, etc.

(Source: National Institute of Statistics and Geography [INEGI], 2009).