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Review Article

The Chilhuacle Chili (*Capsicum annuum* L.) in Mexico: Description of the Variety, Its Cultivation, and Uses

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The chilhuacle chili (*Capsicum annuum* L.) is a Mexican native variety whose production has been highly valuable because it is the main ingredient of the Oaxacan black mole, a typical Mexican dish. It is basically grown in the Cañada Region of the State of Oaxaca, Mexico, within the Tehuacán-Cuicatlán Biosphere Reserve. Importantly, it is cultivated under traditional agricultural systems, where a range of agronomic constraints associated with the production process and the incidence and severity of pests and diseases represent significant impediments that hinder the yield potential. Additionally, the genetic basis of the crop is highly restricted. Under such environmental and production conditions, the mean crop yield of chilhuacle chili can reach $1\,t\,ha^{-1}$ of dehydrated fruits, which can be used in the food, chemical, and pharmaceutical industries. In this review we summarize the current progress on chilhuacle chili cultivation and outline some crucial guidelines to improve production, as well as other research topics that need to be further addressed.

1. Introduction

Chilies belong to the genus *Capsicum* (Solanaceae family), which is one of the most cultivated groups of species in the world. These diverse species are grown worldwide for vegetable, spice, ornamental, medicinal, and lachrymator uses and are a significant source of vitamins A and C [1, 2]. *Capsicum* is native to the tropical and subtropical Americas, and the majority of the genetic diversity is concentrated in Bolivia, Peru, Brazil, and Mexico. This genus comprises over 30 species, and *C. annuum* is the most widely cultivated and economically important one. *Capsicum annuum* was domesticated in Mexico thousands of years ago and includes both sweet and spicy fruits, with a myriad of shapes, colors, and sizes [2–7].

The remnants of wild chili peppers recovered at various locations in Coxcatlán cave in the Tehuacán Valley, Mexico, and those identified in the Guilá Naquitz cave in the Oaxaca Valley, Mexico, indicate that chilies were harvested in the wild in Mexico more than 8,000 years ago, and their domestication and cultivation for the first time in Mesoamerica occurred approximately 6,000 years ago [2, 8]. It is believed that seed dispersal was performed by wild birds, while selection and domestication by humans gave rise to various types of fruit morphology and degrees of pungency [1, 4]. The chilhuacle chili is an endemic crop of the Cañada Region in the State of Oaxaca, Mexico, the only place in the world where it is produced.

The main markets to which Mexican chilies are exported include the United States, Japan, Canada, the United Kingdom, and Germany [9]. Currently, Mexico is the second world's leading exporter of fresh chilies and the sixth largest exporter of dehydrated chilies. By entering this thriving export market, chilhuacle chili producers may find new market niches and expand their production and marketing potential. However, new technologies and innovations have to be developed to support a possible rise in production and commercialization. The locations where it is mainly cultivated are San Juan Bautista Cuicatlán, Tomellín, Valerio Trujano, Santa María Tecomavaca, San José del Chilar, and

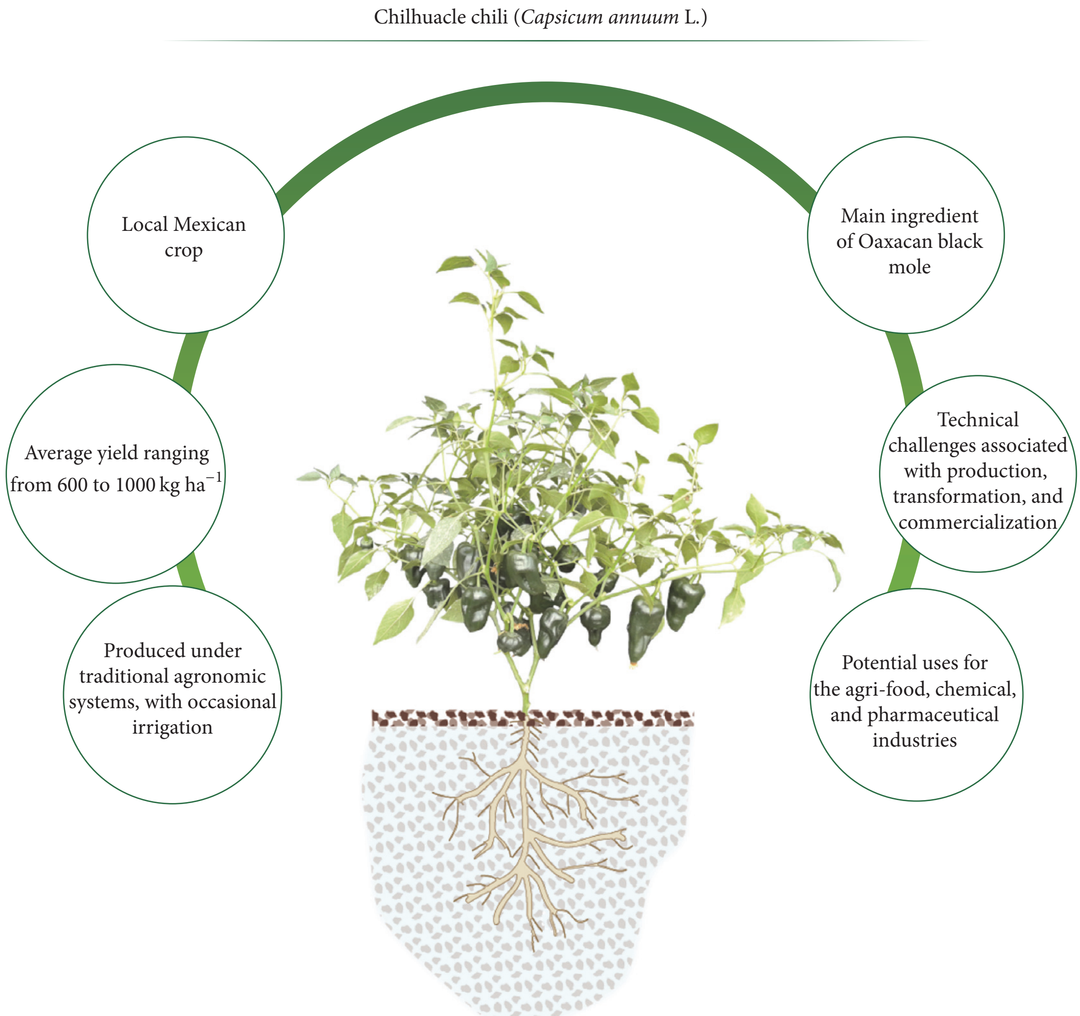

Figure 1: Summary of chilhuacle chili production, yield, and potential uses.

Santiago Dominguillo, all within the Cañada Region in Oaxaca, Mexico.

The importance of the chilhuacle chili lies in its international recognition as a culinary spice in the preparation of the famous "Oaxacan black mole" (Mole Negro Oaxaqueño), using dehydrated fruits, while an alternative local dish called "Texmole" is prepared with fresh chili. A graphical abstract summarizing some important issues concerning the chilhuacle chili is displayed in Figure 1.

The culinary and gastronomic value lies in the fact that this chili has unique characteristics in terms of aroma, color, and flavor, which are enhanced by the dehydration process [3]. The culinary use of the chilhuacle chili in Oaxacan regional cuisine has been recognized as a component of Mexican cuisine by the Intangible Cultural Heritage of Humanity for the Organization of the United Nations for Education, Sciences and Culture (UNESCO) [10], which emphasizes the importance of this crop. Despite its importance in Oaxacan cuisine and the demand for it, chilhuacle chili is a species that tends to be increasingly less cultivated and is in danger of extinction according to SAGARPA Regional Offices' Joint Information System (Sistema de Información Coyuntural de las Delegaciones SAGARPA, SICDE: http://www.sicde.gob.mx) [11]. According to López-López et al. [12], new strategies for growing chilhuacle chili are needed because there are currently only a few producers who cultivate it in the state of in Oaxaca. In this state, the development and generation of technological packages are practically nonexistent, which is reflected by the scarcity of research on production systems. For these reasons, it is necessary to undertake various strategies to deepen our knowledge of this crop to provide a solid foundation that permits its sustainable utilization. This research highlights different aspects of this crop generated in the areas where it is cultivated.

2. Culinary Uses of Chilhuacle Chili by Indigenous People

The chilhuacle chili, or huacle chili, is mainly used by the Cuicatecos and Chinantecos native groups of Mexico. According to the National Commission for the Development of Indigenous Peoples (CDI: http://www.cdi.gob.mx) and the National Population Council [13], the Cuicateco population is slightly greater than 13,000, while the Chinanteco region has over 137,000 inhabitants, distributed mainly in Northern Oaxacan. The chilhuacle chili is mainly used by these towns for religious purposes at festivals such as the Day of the Dead, the Days of the Patron Saints of Towns, Christmas, and New Year's festivities, as well as family celebrations such as weddings and birthdays [14].

The chilhuacle chili provides unique flavor characteristics, and each dish is recognized by the manner and the place in which it is prepared. Oaxacan black mole is the most widely recognized culinary specialty in which this chili is used; when it is prepared with traditional methods, a wide variety of local and international ingredients, such as peanuts, walnuts, almonds, cinnamon, cloves, seedless raisins, oregano, and Oaxacan table chocolate, is used [15]. As a result of its high demand and its increasing scarcity, the price of dehydrated fruits can vary between 25 and 38 US dollars per kilogram, making it one of the most expensive ingredients in Mexican cuisine. As an alternative, and with the aim of lowering production costs, restaurants have opted to substitute the chilhuacle chili for the guajillo and ancho chilies to prepare black mole; however, this also affects the original flavor and consistency of this variant of Mexican mole.

3. Main Topics Addressed in the Literature on Chilhuacle Chili

Because of its importance, there are various publications on the culinary richness of this chili. The fruit is scarce, produced during a short period, and its Nahuatl name suggests a pre-Columbian domestication [16, 17]. There are three known types of chilhuacle chili cultivar that are differentiated by their color: the yellow, red, and black chilies. These characteristics impart a deep and intense flavor to the famous Oaxacan black mole dish [18]. The chilhuacle chili is one of the most widely consumed species (though not in large volumes) in the State of Oaxaca, in addition to other chilies, such as the agua, pasilla, guajillo, tabiche, tusta, and paradito [19]. This widespread consumption ensures that the diversity of local types of chilhuacle chili is not lost in these various localities, which promotes conservation based on consumption. Chili continues to be a catalyst in the Mexican kitchen and has been employed for thousands of years to modify the flavors of the basic diet of the country, surviving throughout the centuries in spite of the introduction and the influence of culinary traditions from other countries [20]. Generally, it is the local chilies that impart a unique characteristic to the regional food, as is the case for the use of the chilhuacle chili to prepare mole in Oaxaca or the Habanero in Yucatecan cuisine.

Other publications consider the chilhuacle chili to be a variety that is in danger of extinction, highlighting the great importance of conducting research into its production system. According to the SAGARPA Regional Offices' Joint Information System [11], Mexico is the center of origin and diversity of *C. annuum* species; however, there is no accurate record of chili varieties, and some of them are cultivated to only a limited extent, thus producing only low yields, a factor driving the high market price, as is the case for the chilhuacle chili. Importantly, chilhuacle chili is itself in danger of disappearing and being replaced by other types of chili. Year by year fewer farmers cultivate it, as a result of migration and farm abandonment because young people are less interested in agriculture. This phenomenon is complex, though main reasons are related to the very low profits farmers obtain from their crops. We think that technology can bring about new tools to farmers to cultivate chilhuacle chili and increase profits.

The cultivation of the chilhuacle chili, and other species, should be preserved and promoted or these chilies could disappear from the Oaxacan fields. This crop can obtain a high market value because of its desired taste and the limited extent of production. Nevertheless, there is a paucity of research on the chilhuacle chili. Among those publications that exist, the literature covers topics related to management and production strategies, culinary uses, and the recovery of genetic resources. This last section aims to emphasize the fact that chilhuacle chili is undergoing the process of extinction, demonstrating the necessity to strengthen efforts to implement strategies for its study and for the purpose of its conservation and sustainable use. In addition to exploring all biological aspects of the chilhuacle chili, technological packages for its production, processing, and sale that are based on technological innovations and improvements in organizational, commercial, and managerial strategies [21] need to be developed.

4. Origin, Taxonomy, and Botany of Chilhuacle Chili

Pungency and color of chili fruits are crucial factors in determining their quality and commercial value. Such characteristics depend on the genotype and time of planting and harvest [22]. In particular, the origin of chilhuacle chili is restricted to the Cañada Region in the Tehuacán-Cuicatlán Biosphere Reserve, which is located in southern Mexico, within the states of Puebla and Oaxaca (Figure 2). Most species that inhabit this region are restricted to the limits of this area and are therefore endemic species [23, 24].

Chilhuacle chili is a cultivar of the species *C. annuum* [25]. *Capsicum annuum* var. *annuum* is the domesticated form and the most important in Mexico and across the globe; it also has the highest morphological variability because it comprises the majority of the chili and pepper types grown in Mexico [26]. In Mexico, the National Commission for the Knowledge and Use of Biodiversity (CONABIO, for its acronym in Spanish) has compiled detailed taxonomic records for *Capsicum annuum* var. *annuum* [27].

The chilhuacle chili is a plant of dichotomous branching. Its root may reach depths of 70 to 120 cm. The bulk of the roots is located within a soil depth of 5–40 cm. The plants have a green cylindrical herbaceous main stem that is semiwoody at the base and slightly pubescent. The growth of the stem is limited, and the stem divides into 3 or 4 branches or secondary stems between the heights of 10 and 40 cm. The dark green leaves are lanceolate or oval, have an entire lamina

Figure 2: Cañada Region in the State of Oaxaca, Mexico, the only place in the world where chilhuacle chili is produced. Cañada Region is located within the Tehuacán-Cuicatlán Biosphere Reserve in southeast Mexico, within the State of Puebla and Oaxaca.

margin, and are weakly pubescent with a nonerect petiole. The flowers appear solitary in the node of branches of the stem, and each branch can have 5 to 6 or more flowers (Figure 3).

Flowers are perfect and regular and composed of 6-7 sepals partially fused together and 6-7 petals. Their position is intermediate, according to the International Plant Genetic Resources Institute [28]. The androecium is composed of 7 equal stamens, bilocular and dehiscence inwards or terminal. The ovary is superior, of 2-3 carpels with a single style and stigma (Figure 4). Chilhuacle chili flowers are self-pollinated, though bees, wasps, and ants may contribute to cross pollination, which is common when it is cultivated under field conditions [17].

During the early stages of growth, the fruit appears round and the calyx covers much of the outside. Subsequently, the fruit acquires an elongated form, with a 4 to 8 mm thick peduncle. When the fruit acquires its final size and shape, the calyx becomes immersed in the fruit and the thickness of the peduncle decreases (Figure 5).

The fruit is a berry in the form of a capsule, with trapezoidal shape and a mean size of 10 cm in length and 8 cm in equatorial diameter. Fruits are usually consumed when they reach maturity (60 to 78 days after pollination (DAP)) and have been dehydrated. Fruit color varies according to developmental stages (Table 1, Figure 6), and this characteristic is crucial to determine the right moment of harvesting.

Changes in color of mature dehydrated fruits are depicted in Figure 7. Once the fruits have been dehydrated, seeds retain their germination capacity for 3 to 4 years [3, 29]. In order to preserve seed germination capacity, local farmers keep seeds within the dehydrated fruits, until the new production cycle starts.

5. Agronomic Practices for Chilhuacle Chili Production

In Mexico, the State of Oaxaca has one of the highest diversity levels of chilies, including chilhuacle chili [30, 31]. Under Oaxacan environmental conditions, some agronomic constraints are associated with the production process of this crop, and the incidence and severity of pests and diseases are among the most significant impediments that hinder the potential of this crop [32].

Chilhuacle chili, as well as soledad, costeño, and agua chilies, which are also native to Oaxaca, are domesticated cultivars grown under traditional agricultural systems, where no sophisticated technologies are used [33]. In the Cañada Region, seeds of this chili are germinated at the end of the dry season (i.e., May). Once seeds germinate, plantlets are transplanted to the crop fields in June and July, during the raining season. Eventually, local farmers irrigate the crop if necessary. Harvest takes place in October, once the rainy season has ended.

The greatest yield of chilhuacle chili has been obtained with a density of 53,000 plants per hectare, although the largest fruits with the greatest dry masses can be obtained at a lower density (i.e., 40,000 plants per hectare) [34]. Furthermore, pruning increases the yield per plant and per unit surface area, although the fruits tend to be smaller [34]. When nutrient solutions are applied during irrigation, the best agronomic responses are observed with the Steiner [35] and Escobar [36] nutrient solutions [29].

When grown under field conditions, this crop performs better in friable and well-drained, sandy loam soils with pH values between 6.5 and 7.5, with a minimum depth of 35 to 50 cm [37, 38], and slopes ranging from 1 to 10%. Luvisols,

Figure 3: Morphology of a mature chilhuacle chili plant and anatomy of fruits. (1) A chilhuacle plant during fruit development. (2) A mature fruit. (3) A stigma. (4) Stamens. (5) Petals. (6) Flowers. (7) Leaves. (8) Cross section of immature fruit showing septum and seeds. (9) Immature seeds of the fruit. (10) Mature seeds are yellow.

Figure 4: Flower developmental stages of chilhuacle chili. (A) Floral bud 1 day after pollination (DAP). (B) 2 DAP. (C) 4 DAP. (D) 5 DAP. (E) 7 DAP. (F) Fruit development 8 DAP.

Cambisols, and Phaeozems are the main types of soils where this chili variety is most often cultivated [32]. The terrains where chilhuacle chili is cultivated are located from 687 to 1085 meters above sea level (masl) [32].

Climates of the region where this variety is produced are predominantly semiarid and warm (BSh climate), with a mean annual rainfall of 450 mm, the majority of which falls between June and September, and a mean annual temperature higher than 22°C, with temperatures higher than 18°C in the coldest month [39, 40].

5.1. Seedling Production. Chilhuacle chili seedling production is accomplished by sowing the seeds in soil, with selected seeds obtained from well-selected mature chilies. The seedbed is prepared in an open (nonshaded) area, and the soil is manually tilled with a hoe or a shovel. For the seedbed, a mixture of one-third of properly composted cattle manure, another third of local soil, and a remaining third of fine sand is prepared. Planting beds of 1 m^2, with 20 cm borders on the sides, are created using this substrate mixture. The seeds are broadcast-sown and covered using a broomstick. The soil should be moist for as long as the seedlings are in the seedbed, without flooding; hence, proper drainage is necessary with light and frequent irrigation. Similar practices for obtaining seedlings of other varieties of peppers native to Oaxaca, such as the soledad and agua chilies, have been described by various nurseries [41]. A solution of propamocarb chlorohydrate

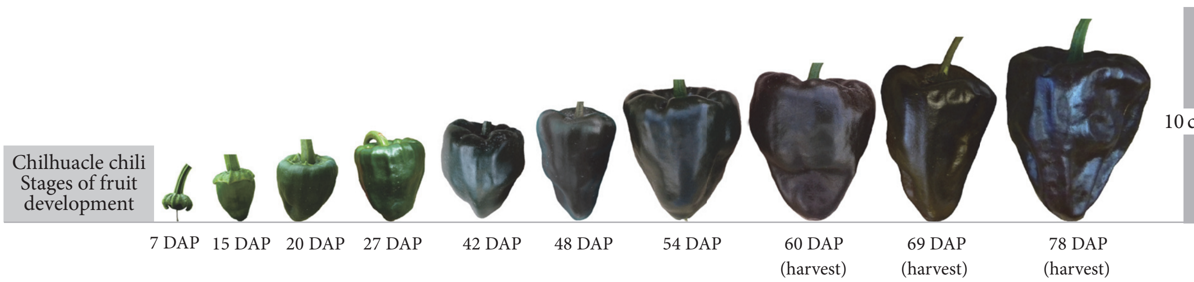

Figure 5: Development of the chilhuacle chili fruit. The fruit develops 7 days after pollination [DAP]. At the beginning of fruit development, the calyx covers a substantial portion of the outside of the fruit (15 DAP). Subsequently, the fruit acquires an elongated form, with a thick peduncle (20 to 27 DAP). When the fruit has achieved its final size and shape, the color is black or very deep purple and the calyx is immersed in the fruit (42 to 54 DAP). Developed fruits can be harvested between 60 and 78 DAP.

Table 1: Chilhuacle chili developmental stages and color changes from immature to mature fruits.

Color scale	Developmental stage	Days after pollination (DAP)	Color			Description of color
			Luminosity	Chroma	Hue	
1	Immature	15	22.8	7.0	139.2	Light green
2	Green	27	22.4	7.1	138.9	Bright green
3	Green-mature	42	22.7	7.5	141.6	Bright dark green
4	Mature	54	21.0	5.3	155.9	Completely dark green

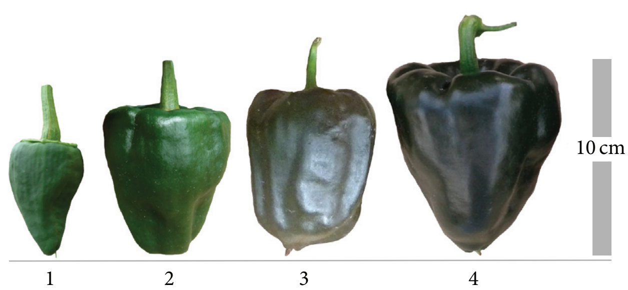

Figure 6: Color changes from immature to mature fruits of chilhuacle chili: (1) Immature fruit. (2) Green fruit. (3) Green mature fruit. (4) Mature fruit.

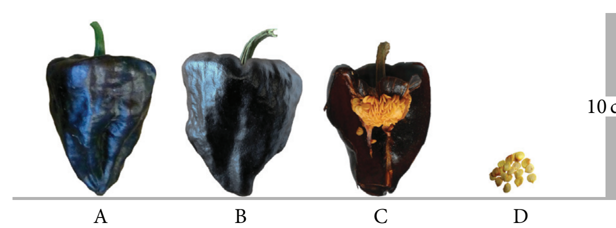

Figure 7: Dehydrated fruit of chilhuacle chili. (A) A mature chilhuacle fruit 78 DAP. (B) A dehydrated fruit. (C) A dehydrated fruit, showing the apex, which consists of a thick pericarp and placental tissue to which the seeds are attached. (D) In mature dehydrated fruits, the seeds are flattened and yellow in color.

(64% aqueous solution) at a concentration of 0.5 g L^{-1} may be applied to prevent fungal diseases when planting chilhuacle chili seedlings in polystyrene trays, with a 1 : 1 mixture of peat : perlite, with 2 seeds sown per cavity in damp substrate and irrigation to saturation [29, 42]. The success of the chili production process lies in the strength and size of the seedling used in planting, which depends on seed quality, seedbed preparation, soil disinfection, nutrient applications, and general handling in the nurseries [43]. Local farmers of the Cañada Region do not disinfect soils, though they use other sustainable practices such as crop rotation.

In our experimental conditions, seedling emergence occurred seven days after sowing, which differs from other chilies such as poblano with a germination period of 9 days [44], mirasol with 10 to 12 days, árbol and ancho chilies with 3 days, and guajillo chili with 4 days to start germination [45].

Under greenhouse conditions, transplantation of chilhuacle chili plants in polythene bags with a sand substrate was performed successfully 57 days after sowing; plants achieved a mean height of 20 cm with 2 true leaves fully formed and extended during this growth period [29]. For seedling growth and development, the choice of substrate is a key factor that contributes to seedling quality [46]. We have observed that the choice of substrate supplemented with 25% Steiner's nutrient solution [47] affects the growth and development of chilhuacle chili plantlets, which is most evident 50 days after planting (Figure 7). Plants that developed in peat were taller and had a greater number of leaves, and the root and substrate remained intact when the seedlings were removed from the seedbed (Figure 8(A)), while those cultivated in agricultural local soil were shorter than those that developed in peat, although the root ball had similar characteristics to those developed in peat (Figure 8(B)). The beneficial effect of peat on plant growth may be attributed to its biological, physical, and chemical properties that improve nutrient availability to plant roots [48], whereas the local soil conferred higher compaction and hence less water and nutrient availability to plants. Tezontle, a Mexican local volcanic gravel, is inert

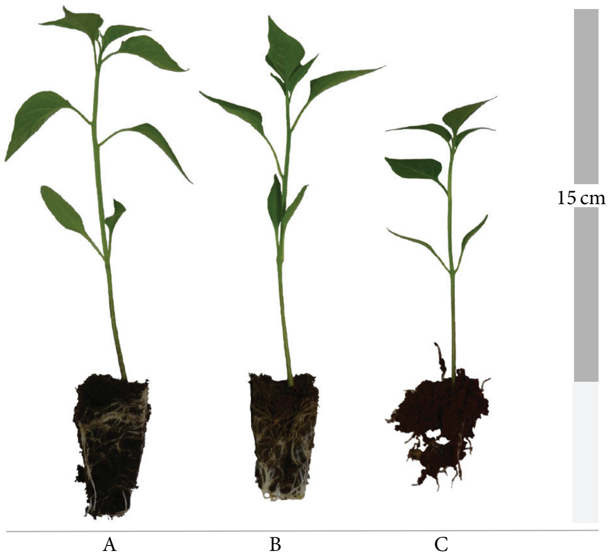

Figure 8: Characteristic chilhuacle chili seedlings and their root balls in three different substrates 50 days after planting. (A) Seedling developed in peat. (B) Seedling developed in common soil. (C) Seedling developed in volcanic gravel. Plants were irrigated every other day with 25% Steiner's nutrient solution.

and its water retention capacity is very low [49]. In our experimental conditions, plants that developed in tezontle as substrate were shorter than those grown in peat or local soil, and the root ball had a lower transplantation value given that it disintegrated easily (Figure 8(C)).

The choice of substrates for planting is crucial because it provides appropriate conditions to the crop for root growth [46]. One of the most globally used substrates for seedling production is peat moss because its main characteristics provide excellent germination and seedling growth. However, the high cost and nonsustainable exploitation of peat are restricting its use [50], which highlights the importance of finding new local substrates that ensure excellent germination of genetic resources such as the chilhuacle chili.

5.2. Chilhuacle Chili Nutrient Management. Chilhuacle chili is mainly cultivated under rainfed conditions, eventually supplemented with irrigation systems. When irrigated, water is applied every 8 days, for a total of 17 irrigations during the crop cycle. The irrigation is applied to small surface areas, ranging from 2,500 to 5,000 m^2, and occasionally on land areas of 1 ha [29]. A chilhuacle chili fertilization program may comprise inorganic fertilizer applications at 25 and 46 days after transplantation, while a number of producers apply 200 kg of 17-17-17 (NPK) fertilizer or 200 kg of urea (equivalent to 92 kg of N ha^{-1}) for each growth cycle [32]. Interestingly, N doses applied by local Oaxacan producers of chilhuacle chili are low compared to that of the recommended fertilizer application for soledad chili (also native to the State of Oaxaca), which are 400, 300, and 300 kg ha^{-1} N, P, and K, respectively, in the municipalities of Loma Bonita, Tuxtepec, Valle Nacional, and Santa María Jacatepec, which have sandy-crumbly and sandy-clayey soil textures [41]. Under this management regime, the mean yield ranges from 600 to 1000 kg ha^{-1} of dehydrated chili [3, 29], with N, P, K, Ca, and Mg being the most important nutrients affecting yields [51]. The fertilization regimes of other varieties of chilies may be relevant to chilhuacle chili production, but regardless of that, soil characteristics must also be taken into account for production purposes. For example, for the cultivation of local and commercial varieties of chilies in Yucatán, Mexico, it is recommended to apply 280-200-330 kg ha^{-1} NPK plus 10 t ha^{-1} of chicken manure distributed in three stages as follows: first, at the time of the transplant, all of the chicken manure and half of the N, P, and K; the second application during flowering, applying 25% of N and 50% of the remaining P and K; and finally, the remaining quantity of N after the third harvest [52]. In the production of mirasol chili in loam-textured soils with a mean organic matter content of 1.93%, pH of 7.8, and electrical conductivity of 0.63 dS m^{-1}, in Zacatecas, Mexico, the application of 200-160-100 kg ha^{-1} NPK + calcium has been recommended [53]. In this variety, the application of 210-150-100 kg ha^{-1} NPK increased the total yield and the plants produced better quality dried fruit [54]. Accordingly, the application of 120-60-00 kg ha^{-1} NPK for mirasol variety cultivated in San Luis Potosí (Mexico) highlands has been recommended to be applied in 2 stages: first, before the third irrigation, half of the N and all the P (i.e., 60-60-00 kg ha^{-1} of NPK) are applied, and the remaining 60 kg of N is applied at the onset of flowering. With this fertilization dosage, the mean yield is 1.2 t ha^{-1} of dry chili at planting densities of 30,000 plants per hectare [55].

In general, yields are affected by various factors including genotype, climate, soil fertility, fertilization dose, pest and disease control and management, and harvesting and processing methods. Regional and seasonal variations in the environment, cultural practices, the availability of N, and the absorption efficiency of N by the plant are also considered to be determining factors for yield [56], although neither the total production nor the productivity per plant or per surface area increases synchronously with nutrient supply [57]. In fact, fertilization can have secondary, often unpredictable effects on growth and yield through changes in growth pattern, plant morphology, anatomy, or chemical composition, which can increase or decrease the resistance or tolerance of plants to biotic and abiotic stress factors [58]. Research approaches that target the *Capsicum* genus that scarcely study genotypes such as the chilhuacle chili are required to determine the precise physical environment and management conditions that should be implemented.

With respect to agronomic management, there are two greenhouse studies of chilhuacle chili. In the first one, different planting densities and the pruning of side stems were evaluated, reporting that the highest yields were obtained with high densities and without pruning, using the Escobar nutrient solution [34, 36]. This solution has been used for the growth of plantings established on substrates such as perlite and rockwool. The solution has the following concentrations (in mEq L^{-1}) of anions, NO_3^- (13.5), $H_2PO_4^-$ (1.5), and SO_4^{2-}

(1.35), and of cations, K^+ (5.5), Ca^{2+} (4.5), and Mg^{2+} (1.5). In the second study, physiotechnical and quality variables of chilhuacle chili fruits from plants cultivated using Escobar [36], Steiner [35], and Urrestarazu [59] nutrient solutions were tested [29]. Plants exhibited a better response to the Steiner and Escobar nutrient solutions as a consequence of the ionic mutual ratio [36], which is defined as a mutual relationship among anions (NO_3^-, $H_2PO_4^-$, and SO_4^{2-}) and a mutual relationship among cations (K^+, $Ca^{2+,}$ and Mg^{2+}). Therefore, if the relationship among them is adequate, the plant can achieve its maximum potential [60]. Although the effects of nutrients on the growth and yield of the chilhuacle chili can be explained in terms of the function of these elements in plant metabolism, in the *Capsicum* genus, the demand for nutrients such as N and K has been observed to increase during the flowering, fruiting, and fruit-filling stages [61]. In varieties of chilies such as jalapeño, habanero, and a number of commercial hybrids, the levels of N and K significantly affect plant growth, stem diameter, number of leaves, fruit yield, pungency, and capsaicin levels [62–64].

5.3. Pests and Diseases. The chilhuacle chili has various problems of a phytosanitary nature, such as the pepper weevil (*Anthonomus eugenii* Cano) and insect vectors of viruses (aphids and whiteflies). The pepper weevil is one of the most important insect pests of this crop [29], especially during the flowering and fruiting stages. The larva of this insect drastically reduces fruit number, causing early fruit drop, premature ripening, and fruit deformation, which together may reduce the harvest by 90% [65, 66]. Although there is no recommended control method described for preventing pepper weevil damage in chilhuacle chili, generally, a chemical control based on chlorpyrifos, oxamyl, and fipronil at doses of 720, 520, and 50 g of active ingredient per hectare, respectively, is recommended [67, 68]. Nevertheless, the best prevention method is to select genotypes displaying resistance against such biotic stress factors. Accordingly, we are currently creating novel genetic diversity using gamma radiation by ^{60}Co and the evaluation of the first-generation of mutant varieties is underway, which may result in a major breakthrough to increase diversity in chilhuacle chili in Mexico.

Though important pests and diseases in chilhuacle chili plants are being documented, only a few insect pests and pathogens have been reported so far. Just recently, we have published the first report of powdery mildew in chilhuacle chili caused by *Leveillula taurica* in southern Mexico [69]. Therefore, more in-depth studies on those phytosanitary problems need to be conducted in order to ensure a sustainable crop production system.

5.4. Fruit Dehydration. The crop is cultivated to produce dried chilies to be sold in local markets in Oaxaca and Puebla, Mexico. Dehydration is performed in areas with slopes greater than 5%, where ripe fruits are placed on stone beds and left under direct sunlight. This procedure has a considerable influence on the color, flavor, texture, and nutritional quality of the dried chilies. This method also prevents any damage associated with excessive moisture [3]. However, the labor is costly and involves a large number of working hours because each day the fruit has to be taken out of the sun, turned over, and stored for the afternoon until a suitable moisture level for sale at the local markets is achieved. Hence, one area for innovation is the postharvest handling procedure, mainly in relation to the dehydration process.

6. Chilhuacle Chili May Be More Than a Spicy Culinary Fruit

In general, products derived from *Capsicum* fruits include fresh, dried, or pickled pepper, ground powders, and processed products such as purees, sauces, and oleoresins. Oleoresins contain a significant amount of esters of capsorubin, capsanthin, cryptoxanthin, zeaxanthin, and other carotenoids [70, 71], used in foodstuff and cosmetics, and serve as a source of the pungent component capsaicin for pharmaceutical products [72, 73] or self-defense weaponry [74]. Bioactive compounds present in *Capsicum* fruits display antioxidant, anticancer, anti-inflammatory, antiulcer, and antiobesity pharmaceutical properties, among others, and they also promise other health benefits [75]. Furthermore, these fruits exhibit a wide range of pharmacological activities, including chemopreventive, analgesic, antilithogenic, antidiarrhoeal, antiallergic, antidiabetic, antihypertensive, hypoglycaemic, antimicrobial, antioxidant, antifungal, and antiviral properties [76].

Compounds known as capsaicinoids cause the pungency of chili pepper fruit. Capsaicinoids include capsaicin, dihydrocapsaicin, nordihydrocapsaicin, homodihydrocapsaicin, and homocapsaicin, with capsaicin being the primary capsaicinoid in chili pepper (i.e., accounting for up to 80% of capsaicinoid content of fruits) [77]. We determined the capsaicinoid concentrations in two groups of mature chilhuacle chili fruits (Table 2). In 78 DAP fresh fruits the concentration of capsaicin (in dry basis) was lower than that observed in dehydrated fruits. Moreover, the concentrations of dihydrocapsaicin and nordihydrocapsaicin, as well as the pungency value, were higher in dehydrated fruits. When comparing these values with other chilies produced in the same region, chilhuacle chili has a higher content of capsaicinoids and pungency value than miahuateco, tecomatlán, and mulato but a lower concentration of capsaicin and less pungency than copi [78]. Our results demonstrate that the concentrations of capsaicin and capsaicinoids and the pungency in dehydrated chilhuacle fruits are higher than those found in other chili varieties including guajillo, ancho, pasilla, and puya. However, values found in fruits of jalapeño, mirasol, morita, serrano, chipotle, de árbol, piquín, and habanero are higher than those found in chilhuacle [79]. Capsaicinoid concentrations in chilies may vary according to the genotype, geographic origin, and climatic conditions where they are produced [80]. Nonetheless, the genotype is the most critical factor [81]. Since capsaicin has therapeutic applications [76–78], chilhuacle chili may deliver diverse health benefits.

Finally, *Capsicum* fruits have an enantiomeric composition of phytochemicals. Many of these are chiral molecules that can exist in plants in different enantiomeric forms, such as the pepper aroma compound linalool [82], which occurs

Table 2: Capsaicin and capsaicinoid concentrations and pungency of different chilies native to Mexico.

Chili variety	Capsaicin (mg kg^{-1})	Dihydrocapsaicin (mg kg^{-1})	Nordihydrocapsaicin (mg kg^{-1})	Pungency (SHU)	Reference
Chilhuacle (78 DAP)	161.0	47.0	9.0	3379	—
Chilhuacle (dehydrated)	235.0	142.0	53.0	6420	—
Miahuateco	63.6	45.5	na	1637	[79]
Copi	267.4	167.7	na	6525	[79]
Native Tecomatlán	54.6	35.8	na	1354	[79]
Mulato	29.5	49.5	na	1183	[79]
Guajillo	22.85	36.85	na	961.13	[80]
Ancho	42.82	42.19	na	1368.60	[80]
Pasilla	49.21	68.76	na	1899.34	[80]
Puya	53.88	67.40	na	1952.61	[80]
Jalapeño	373.51	210.40	na	9400.83	[80]
Mirasol	353.77	231.70	na	9426.09	[80]
Morita	338.25	334.94	na	10838.24	[80]
Serrano	627.48	399.77	na	16538.78	[80]
Chipotle	883.04	552.65	na	23114.68	[80]
De Árbol	1293.36	641.74	na	31155.10	[80]
Piquín	2656.74	1031.57	na	59381.77	[80]
Habanero	9097.35	4023.63	na	211247.65	[80]

SHU: Scoville Heat Units. na: not available. DAP: days after pollination.

naturally in one enantiomeric form but experiences racemization during postharvest treatment [75, 83]. In the case of the chilhuacle chili, all these chemical and pharmaceutical properties need to be studied in greater depth in a new research environment improved by the development and validation of new analytical protocols.

7. Conclusions and Perspectives

The chilhuacle chili is recognized as a unique ingredient of Mexican cuisine, especially as the characteristic seasoning of Oaxacan black mole. As an endemic genetic resource of Mexico, it is necessary to implement various innovative strategies throughout the value chain that will ensure its conservation and sustainable use.

For the thematic review of the chilhuacle chili, only 15 publications from Mexico were found, which demonstrates the clear need to further study this crop and its uses. In environmental terms, the effects of global climate change on agriculture in Mexico could reduce national agri-food production by 25.7% by 2080 [84], if relevant strategic measures are not taken to address this global phenomenon. On the other hand, the country's population continues to grow, which also makes it necessary to develop efficient strategies that ensure food and energy security. An advantage in terms of global politics is that Mexico has provided numerous nutritional elements that have enriched international gastronomy because, as a megadiverse country, this nation is the center of origin and genetic diversity of numerous crops such as corn, squash, beans, and chilies. This diversity of food crops has long been valued by international agencies such as UNESCO, which recognized Mexican food as an Intangible Cultural Heritage of Humanity in 2010. Oaxacan black mole and the chilhuacle chili have high nutritional and gastronomic values that justify any innovation initiative undertaken to improve knowledge of their cultivation and use. Nevertheless, only a few producers are growing this variety to date. In the face of these challenges and opportunities, the lines of research, technological development, and innovation that may be proposed can range from basic studies on the genomic, biochemical, and genetic variability of crop physiology to issues related to its use and possible new applications. Characterization of nutritional and nutraceutical properties, development of new drying and processing strategies for the product, improvements in the organization and training of producers, exploration of new market niches and international markets for chili and Oaxacan black mole, and the general management of the products obtained are all required. The benefits of these initiatives could be obtained by the original producers through, perhaps, the opening of Oaxacan cuisine gourmet restaurants managed by the producers themselves. This last possibility represents one of the major challenges for the development of indigenous peoples and the promotion of their cuisine internationally because, in addition to their high linguistic diversity (considering that each Chinanteco town has its own linguistic variation) and cultural diversity, there are serious limitations in terms of education level, mastery of other languages, and resistance to organization and trade, among others. Therefore, any strategy that aims to improve the use and exploitation of this chili genotype will have to consider the human factor as a determinant of the success of such projects. Our team is currently creating the generation of new mutants, with the aim of increasing the genetic diversity of chilhuacle chili in Mexico, and we have published the first report of powdery mildew in chilhuacle chili caused by *Leveillula taurica* in southern Mexico. In terms of technological innovations, studies that evaluate the oil content of the seeds are required to support their use as seasoning and flavoring ingredients, while alternative uses of the fruit and seeds in the chemical and pharmaceutical industries await further investigation. The generation of standards for good agricultural practices, fair trade, and the appropriate integration of the links in the value chain will help to better position and protect the product in the marketplace.

Disclosure

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Competing Interests

The authors declare that they have no conflict of interests regarding the publication of this work.

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