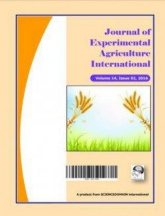

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# Pecan: from Research to the Brazilian Reality

**Mauricio Gonçalves Bilharva[1*], Carlos Roberto Martins[2], Jonas Janer Hamann[3], Diniz Fronza[3], Rudinei De Marco[1] and Marcelo Barbosa Malgarim[1]**

*[1]Federal University of Pelotas (UFPel), Pelotas, Brazil.*
*[2]Brazilian Agricultural Research Corporation (EMBRAPA), Pelotas, Brazil.*
*[3]Federal University of Santa Maria (UFSM), Santa Maria, Brazil.*

***Authors' contributions***

*This work was carried out in collaboration between all authors. Authors MGB and CRM designed the study, wrote the protocol, and wrote the first draft of the manuscript. Authors RM and MBM managed the analyses of the study. Authors JJH and DF managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

Cultivation of pecan trees has increased in Brazil, mainly in the south, in recent years. Despite investments – triggered by the demand and promising market– made by both small and large farmers, actual productivity has still been below its potential. Lack of technical information not only about the culture of pecan trees but also about the development and adequacy of technologies, which are appropriate to the edafoclimatic conditions found in the south of Brazil, corroborate low productivity and poor investments in the sector, mainly preventing production from supplying the internal market. Some pioneering initiatives in the south of Brazil and positive experiences in neighboring countries, such as Argentina and Uruguay, have shown the potential to cultivate pecan in the region. This study aimed at introducing and analyzing the development of researches, general characteristics of the culture, the evolution of cultivation and dissemination of pecan trees in Brazil, mainly in the south of the country.

**Corresponding author: E-mail: maugb88@hotmail.com, mauriciobilharva@gmail.com;*

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## 1. INTRODUCTION

Interest in cultivation and consumption of nuts, such as pecans, has increased considerably worldwide in recent years [1]. Scientific evidence of benefits of nuts, since they are healthy and nutritive food in the human diet, has increased consumption and, consequently, its demand [1,2,3,4]. Interest in cultivating pecan trees (*Carya illinoinensis*) and producing pecans, mainly in southern Brazil, has increased [5] due to favorable climatic conditions and as the result of increasing consumption and fruit appreciation [6,7]. Even though Brazil has been a reference in the cultivation of several fruit trees [8] and has got international recognition, the same does not happen regarding pecan production, which is below the amount needed for the country's consumption. The Brazilian market has been historically supplied by other countries; in the last 10 years, there was 40% increase in expenses with nut importation [9].

The pecan tree (*Carya illinoinensis* (Wangenh.) K. Koch (Jungladaceae) is an important fruit species which predominates in temperate regions in the northern hemisphere [5,10,11]. It is a high deciduous tree that fruits for a long time. It is native to the United States and Mexico but, when it got popular, it triggered cultivation in several countries in different continents, such as South America, where it spread to Uruguay, Argentina, Chile, Peru and Brazil [6,12,13,14,15]. The culture has expanded in China, South Africa, Australia, Argentina, Uruguay and Brazil lately [16].

In Brazil, it was introduced in São Paulo (SP) state in 1870 by North-American immigrants but it only started to be commercially explored around 1960-70, from Minas Gerais (MG) to Rio Grande do Sul (RS) states [17,18]. At that time, several orchards – which stretched over 17,000 ha [19] – were implemented, mainly in the south of Brazil. However, the project was affected by lack of support, information and research that could base cultivation [20,21,22]. The estimate is that there are about 10 thousand ha of pecan trees, mostly cultivated by small farmers and their families, whose properties range from 4 to 15 ha. Production in RS state stands out since it is the largest producer of pecans in Brazil in more than 5 thousand ha, followed by Paraná (PR) and Santa Catarina (SC) states [7].

Even though technologies used for cultivating pecan trees have been established for more than 100 years in Brazil [21], there is scarcity of scientific publications which take into account the country's edafoclimatic conditions [23]. It shows needs and obstacles related to pecan cultivation and production.

This review paper aimed at introducing information about the evolution of pecan culture in recent years. It highlights some studies that were carried out in Brazil and discusses some production bottlenecks, besides pointing out some challenges and opportunities regarding pecan production in the country.

## 2. NUTS: "DRY FRUITS"

Nuts, also known as dry fruits, have been defined as the portion of edible seeds, with low water content and considerable amount of oil, which are usually consumed dry [24]. Peanuts (*Arachis hypogaea* L.), almonds (*Prunus dulcis*), hazelnuts (*Corylus avellana*), Brazil nuts (*Bertholletia excelsa* H.B.K.), cashew nuts (*Anacardium occidentale* L.), macadamia nuts (*Macadamia integrifolia* Maiden & Betche), walnuts (*Juglans regia* L.), pine nuts (*Araucaria* spp.), pistachio (*Pistacia vera* L.) and pecans [*Carya illinoinensis* (Wangenh) K. Koch] are the most common nuts, according to the [25].

In Brazil, the main ones are cashew nuts, Brazil nuts, macadamia nuts and pecans [26], even though they have adapted to regions with different conditions. Regarding cashew and Brazil nuts, they have developed in the north and northeast, where the climate is tropical, while macadamia nuts and pecans are more common in the south and southeast, in regions whose climate is subtropical and temperate (usually mild temperatures).

Dry fruits have considerable contents of unsaturated fat, proteins, vitamins (A, B and C), minerals (calcium, phosphorus, iron, sodium and potassium) (Table 1).

Fatty acids in pecans, mainly oleic and linoleic ones, have from 16 to 18 carbons. Besides, pecans contain tocopherol, which is a natural antioxidant [31,32], and phytochemicals (flavonoids, carotenoids and phytosterols). They also have cardioprotective, anticarcinogenic and anti-inflammatory activities. [33] points out that pecans have polyphenols, which exhibit antioxidant activity.

**Table 1. Nutritional properties of dry fruits (hazelnut, Brazil nut, macadamia nut, pecan, walnut and pistachio)**

| Components (%) | Hazelnut[1] | Brazil nut[2] | Macadamia nut[13] | Pecan[234] | Walnut[1] | Pistachio[13] |
|---|---|---|---|---|---|---|
| Water | 5.0 – 5.8 | 4.0 | 1.1 – 2.0 | 3.4 -6.0 | 3.0 – 5.0 | 5.3 |
| Protein | 12.6 – 15.0 | 15.0 | 7.9 – 9.3 | 9.2 -14.0 | 14.8 | 19.3 |
| Lipid | 61.0 – 62.4 | 63.0 | 76 – 78.6 | 59.0 – 72.0 | 64.0 | 52 – 53.7 |
| Carbohydrate | 16.7 – 17.0 | 29.0 | 7.5 – 13.8 | 15.0 – 18.0 | 16.0 | 19.0 |
| Vitamins and minerals | % | % | Mg | Mg | % | Mg |
| Vitamin A | <1 | - | - | 130 | 0,6 | 230 |
| Thiamine, B1 | 43 | - | 0.215 | 0.86 | 24 | 0.67 |
| Riboflavin, B2 | 7 | - | 118 | 0.13 | 8.1 | - |
| Niacine, B3 | 9 | - | 1.59 | 0.9 | 5.0 | 1.4 |
| Vitamin C | 10 | - | - | 2 | 4,4 | - |
| Calcium | 11 | 0.15 | 0.06* | 73 | 12 | 131 |
| Phosphorus | 41 | 0.88 | 0.24* | 289 | 48 | 500 |
| Iron | 26 | 0.0023 | - | 2.4 | 31 | 7.3 |
| Sodium | 0 | 0.001 | - | Traces | - | - |
| Potassium | 19 | 0.67 | - | 603 | 9.6 | 972 |

*[1][27]; [2][28]; [3][29]; [4][30]*

According to [30], pecan consumption mitigates the incidence of certain diseases, such as Alzheimer's, Parkinson's and other degenerative ones.

Besides the fruit itself, pecan shell can also be used, since it has antioxidant activity [33,34] and considerable amount of fiber, i. e., 48.6% [32]. Gallic acid accounts for 78% of the phenolic composition [33].

Benvegnú et al. [33] studied the effect of the aqueous extract of pecan shell on the mitigation of the effect of cyclophosphamide, in situations in which it is used as a chemotherapeutical substance that is toxic to some organs. [35] stated that the aqueous extract of pecan shell exerts an effect on the protection against signs of anxiety during abstinence of secondhand smoke in mice.

A recent meta-analysis of nut consumption provided more evidence of the fact that it may mitigate risks of stroke, cardiovascular diseases and cancer, besides mortality due to diabetes, respiratory and infectious diseases [1].

## 3. THE GENUS *CARYA*

The pecan tree [*Carya illinoinensis* (Wangenh) K. Koch] belongs to the family Juglandaceae, which has six genera and approximately 100 species [36].

Regarding the genus *Carya*, it has about 20 species, even though few of them yield edible nuts. The following species yield edible nuts: *C. cordimorfis* (Wang) Koch, *C. glabra* (Mill) Sweet and *C. laciniosa* (Wang) Sarg.. Their common names are bitternut, sweet pignut and kingnut, respectively [29].

Sparks [11] has reported that pecan trees originate from indigenous regions that lie along the Mississippi river in the United States of America. Their fruits are part of the diets of several animals, such as birds, foxes, squirrels, opossums, wild pigs and raccoons, besides humans who have eaten them for more than 10,000 years due to their nutritional value, which is the reason that enabled their geographic dispersion [37]. According to [12], *C. illinoinensis* is native to the United States of America and stretches over a broad region from the south of Texas to the north of Iowa. The author also mentions that, because it is a vast region, there is also much disparity among ripening levels of nuts in the country's different regions.

There are more than a thousand varieties that have different fruit shapes, nut quality, tree architecture and reproductive features [38]. This fact is due to the high gene segregation index, as the result of sexual reproduction by seeds, which is the main propagation method [39].

The arrival of pecan trees in Brazil is related to the American Civil War. After the war that reduced the American population, some families decided to leave the United States. Dom Pedro

II, the Brazilian emperor, searched for men who were specialized in cotton cultivation and offered inexpensive land and tax exemption. As a result, Americans came to Brazil, lived in Santa Bárbara d'Oeste and Americana, two cities located in São Paulo state, and developed the cotton culture, besides introducing other cultures, such as watermelon, peach and pecan [16].

## 4. CHARACTERISTICS OF THE PECAN TREE FRUIT

Fruits of pecan trees have been characterized as drupes which grow in bunches that may hold from three to eight nuts. Fruits are dark brown with black spots [40]. Shells (the epicarp) are elliptic; their outermost layer is convex whereas their inner one is concave. Their shapes vary from globelike to ovoid and the epicarp usually consists of four sections [41].

According to [42], self-pollination occurs when there is increase in endogamy; it results in production of small fruits, low yield of almonds and increase in the thickness of the nut shell. Pecan tree cultivation has increased in Brazil in recent years, mainly in Rio Grande do Sul. Despite investments – triggered by the demand and promising market for pecans – made by both small and large producers, actual productivity has still been below its potential. Annual yield is estimated to be between 600 and 1000 $kg.ha^{-1}$, whereas other countries outyield this production, e. g., Chile: from 1500 to 3000 ($kg.ha^{-1}$); Australia, from 2000 to 2500 ($kg.ha^{-1}$); USA, from 1500 to 3000 ($kg.ha^{-1}$); Mexico, from 700 to 1500 ($kg.ha^{-1}$); and Argentina, 2000 ($kg.ha^{-1}$) [22,43,44,45,46]. In many countries, a semi-extractivist system, with no adequate plant management, yields nuts of poor quality and creates problems regarding culture alternation. Even though some factors may lead to low productivity, quality and yield, lack of technical information about the pecan tree culture, such as the need to implement grafted seedlings and different and complementary varieties in pollination, ends up contributing to this situation.

## 5. CULTIVARS

The following 41 cultivars can be found in the national index of registered cultivars (RNC, in Portuguese) [47]: Barton, Brooks, Caddo, Cape Fear, Cherokee, Chetopa, Chickasaw, Choctaw, Clark, Curtis, Davis, Desirable, Elliott, Farley, Forkert, Giles, Gloria Grande, Gormely, Jackson, Jenkins, Jubilee, Kiowa, Mahan, Major, Moneymaker, Moore, Oconee, Owens, Patricks, Pawnee, Peruque, Pitol 1 (Improved), Pitol 2 (Imported), Posey, Prilop of Lavaca, Shawnee, Shoshoni, Sioux, Stuart, Summer and Woodroof. Only two out of 41 cultivars were selected in Brazil: Pitol 1 and 2.

Besides these cultivars, both Imperial and Success have been cultivated, even though they are not registered in the RNC. Some authors disagree regarding the most common cultivars used in Brazil. [48] highlights American cultivars Barton, Caddo, Cape Fear, Choctaw, Moneymaker and Shawnee. [26] designates cultivars as producers (Barton, Desirable and Melhorada) and pollinators (Choctaw, Imperial, Importada, Shawnee and Stuart). [49] states that Barton, Choctaw, Shawnee and Stuart are important cultivars in Brazil. [50] report that Burkett, Frotscher and Moneymaker are the most common ones in Paraná state. There is consensus regarding the fact that a set of cultivars, which is adequate to the technological level, has neither been defined, mainly regarding adaptation and tolerance to climatic and biological adversities, nor had its productive and qualitative potential studied in the region. Thus, good production levels cannot be reached in a sustainable production system. Besides, some factors, such as cultivation in excessively humid places, problems with plagues and diseases and inadequate use of practices and culture management, individually or collectively, show the technological level that reflects decrease in production and quality of harvested fruit.

Pecan trees undergo a morphological phenomenon called dichogamy, in which staminate and pistillate flowers are feasible in different periods, so as to avoid self-pollination. There are protandrous cultivars (Group I), whose staminate inflorescences release pollen before pistillate ones get receptive. In protogynous cultivars (Group II), pistillate inflorescences get receptive before catkins (staminate inflorescence) release pollen. Since this phenomenon is common in the species, pollinating cultivars must be implemented in the orchard so as to offer pollen to the pollination of the cultivar called "producer" [51].

**Table 2. Fruit Mass (FM); Hazelnut Mass (HM); Shell Mass (SM); Yield (Y) and the number of nuts per kilogram**

| Cultivars | FM | HM | SM | Y | Nuts/KG |
|---|---|---|---|---|---|
| Barton[1] | 7,52 – 11,72 | 4,08 – 4,71 | 3,43 – 4,71 | 54,19 | 132,97 |
| Choctaw[1] | 9,87 | 5,21 | 4,66 | 52,65 | 101,52 |
| Imperial[2] | 10,02 | 5,46 | 4,56 | 54,49 | 100,45 |
| Importada[2] | 7,37 | 4,09 | 3,28 | 55,50 | 137,53 |
| Mahan[2] | 7,93 | 4,54 | 3,39 | 57,12 | 128,61 |
| Melhorada[2] | 9,45 | 5,22 | 4,23 | 55,24 | 107,05 |
| Moneymaker[2] | 7,41 | 3,51 | 3,89 | 47,36 | 137,41 |
| Shawnee[1] | 8,28 | 4,7 | 3,57 | 56,69 | 122,15 |
| Stuart[1] | 10,72 | 5,38 | 5,33 | 49,84 | 93,31 |

*[1][49] [2][52]*

Fundamental criteria for the choice of cultivars to be implemented are their resistance to scab and preferably precocious production. Above all, it is essential to know the characteristics, such as size, nut yield and quality, of the cultivar fruits [26].

Some authors have already characterized the fruits of some cultivars implemented in Brazil, as shown in Table 2. [49] recommended the cultivar Stuart in case direct sales of fruits are linked to yield, since it needs fewer number of pecans than others to yield a kilogram. However, in process industries, both cultivars Barton and Shawnee are recommended mainly because their fruits have lower amount of shell than others. [52] evaluated sample dimensions of pecan mass and diameter. The cultivars that had the highest fruit mass (FM), Nut mass (NM) and shell mass (SM) were Barton, Importada and Melhorada.

## 6. PHENOLOGICAL ISSUES

Since pecan trees are native to North America, mainly to the United States and Mexico, their phenology is well characterized. Because Brazilian conditions differ from the ones of their origin, relevant studies are needed. However, they are still scarce in Brazil. Knowledge about phenological behavior and floral compatibility among cultivars is an essential factor in pollination and good fruiting [53].

However, [16] carried out a comparison between the weather in the south of Brazil and in the south of Georgia (GA), USA, and showed that it is similar, thus, enabling information on this state to be used in Brazil.

Tolerance to temperatures of pecan trees varies greatly, since, in winter, they demand temperatures below 7°C, whereas in the dormant period they need from 50 to 600 chill hours, at temperatures below 7.2°C [20,44,54,55].

Since few chill hours lead to irregular budding, droopy leaves, few ramifications and disuniform flowering, pecan trees may have low yield.

Pecan cultivation in Brazil basically takes place in both southern and southeastern regions. However, its production is mainly concentrated in the three southern states (Rio Grande do Sul, Santa Catarina and Paraná). Just recently have other states in other Brazilian regions implemented small areas, even though reports of the species adaptation (due to cold hours) have not been published yet.

The concentration of plantations in the Brazilian southern region is basically due to edaphoclimatic conditions which are favorable to the development of the plant, especially in relation to the requirement of accumulation of cold hours during the winter. However, within a state, there is great variation. For example, in Rio Grande do Sul, there are regions that can accumulate approximately 600 cold hours, while others do not reach 200 hours [56]. According to [20], they are satisfied with the number of hours cultivation implemented in Rio Grande do Sul, i. e., 400 hours. However, according to [22], it has achieved good production in regions in the state where the accumulation is from around 100 to 200 hours. However, in Brazilian conditions, there is still need for more information and follow-up on the adaptation and development of pecan cultivars cultivated in the different Brazilian regions.

Pecan tree budding is developed during ecodormancy and is related to alpha-amylase activity [57]. Productive potential of nuts is

determined when dormancy ends and entirely connected to growth conditions in the season of the previous year. Nut production is related to the end of dormancy, which is determined by the climate factors of the growth season of the previous year, mainly, the female flowering stage, since it depends on substrates accumulated in the crop of the previous year [58].

The need for cold hours (temperatures equal to or below 7.2ºC) during the winter depends on the cultivar, however, agricultural years with a total of hours below the minimum required number can cause physiological disturbances, low percentage and irregularity of bud and consequently reduction of production. As a practice to mitigate this event, in regions where the accumulation of cold is insufficient, it is necessary to use chemicals, such as hydrogen cyanamide (Dormex®) plus mineral oil, or other products, such as garlic extract (which still needs further studies), to provoke the stimulation of budding in pecan trees. Hydrogenated cyanamide develops an action similar to that produced by cold in the reduction of the enzyme catalase in plant tissues, with the increase of pentose phosphate activity, inducing the breakdown of dormancy in plants.

The use of products, such as hydrogen cyanamide, in cold low-lying areas is considered effective to prevent numbness of many fruit trees from happening and may partially replace the need for cold [59]. Although its mode of action is not entirely clear, it may be related to the effects on the respiratory system of cells and to interference in some enzymatic processes that control the rest of the plant, such as catalase activity [60].

Studies of hydrogen cyanamide carried out in Mexico have shown increase in sprouting, high number of nuts and harvest anticipation [61,62]. In Brazil, breaking dormancy in pecan culture has not currently been a common practice because there are few studies of different products, dosages, time and form of application. Therefore, it should be better studied and given due importance, especially in years with atypical winters (low accumulation of cold hours) or in Brazilian regions with mild winters.

Besides, the colder the winter, the less heat is needed for budding in spring [11]. According to [63], the phenological cycle takes place due to the vegetative and reproductive growth and ends in senescence.

Pecan trees are monoicous plants whose staminate and pistillate inflorescences are separated, but both are found in a plant. According to [64], the catkin-like staminate inflorescence bears two or three catkins. They have from 72 to 123 individual flowers [22]. According to [19], the period of pollen dispersal may range from 8 to 15 days, depending on the cultivar. Pistillate inflorescences show little evidence, since they are distributed on lateral terminal branches, and have from two to ten flowers, whose variable colors depend on the cultivar [41].

In the fruiting period, the ideal temperature (monthly average) is between 24ºC and 30ºC. In summer, mainly in the period of pecan filling, high maximum temperatures lead to decrease in fruit size and affect oil accumulation. In addition, they promote premature fruit drop [20].

Nut germination still in the tree (viviparity) causes potential loss to harvest and affects both yield and quality of nuts, since some cultivars and orchard sites may be more prone to viviparity. In addition, management practices, such as nitrogen fertilization and irrigation practices, may aggravate this problem [65, 66]. Therefore, the choice of the site and cultivars which are less susceptible to viviparity, adequate management of fertilization and irrigation, fruit thinning and early harvest, that is, the beginning of the opening of the nut capsule, are alternatives that must be adopted to minimize germination of fruits before becoming detached from the parent plant.

Although viviparity is observed in some orchards in Brazil, especially in hot and humid autumnal (April - May) years, it seems that the cultivars and the environmental conditions in pecan cultivated regions do not cause great production losses. Even so, quantitative surveys and further detailed information on this problem in the Brazilian orchards are needed.

Most cultivars have a long fruit ripening period, i. e., between 180 and 210 days, from fecundation to harvest [11,20]. Pecan ripening takes place from March to May, even though there are some differences among harvest periods in distinct regions in Rio Grande do Sul. For instance, harvest in the region where Santa Maria (latitude 29°S) is located occurs about 15 days before the one in the region around Pelotas (latitude 31° S).

## 7. EDAFOCLIMATIC ZONING OF PECAN TREES

[26] carried out a study of pecan tree zoning in Rio Grande do Sul state and classified them into two classes of risk: low and very low. The latter was then divided into low-A and low-B. In Rio Grande do Sul, 41.8% of the territory has very low risk whereas 51.6% has low-A risk, whose characteristic is the possibility of draught and excess of air relative humidity. Low-B risk accounts for 6.6% of the state and means lack of chill hours. The author highlights that cultures may be grown at both risks (low-A and low-B), even though pecan yield may be affected. Besides, studies of cultivars that endure adverse conditions are needed so as to better adapt them to certain regions.

In addition to this investigation, studies of the edafoclimatic zoning of the culture must be carried out not only in order to guide public policies and financial, extension and technical assistance institutions, but also to conduct land-use planning in areas that can be sustainably explored. Since edafoclimatic zoning takes into account phenological, climatic and soil characteristics simultaneously, it mitigates risks because of the regionalized scale. Definition of edafoclimatic zoning of pecan trees in southern Brazil is premised on the sustainable management of the culture because it guides land-use planning [40] and provides information – about areas where sustainable cultivation can be better developed – to financial institutions, public policies, technical assistance and the whole society. So far, pecan trees have been planted with no orientation, a fact that has often led to economic and/or environmental losses because cultivation occurs in inappropriate areas and affects natural ecosystems.

## 8. PROPAGATION

Pecan tree seedlings are obtained by a vegetative propagation process, i. e., grafting [67]. In the USA, production of pecan tree seedlings by grafting started in 1822 due to increase in producers' demands [16]. Rootstocks are yielded by sexual propagation, i. e., by pecan germination [67]. Seeds that are selected to yield rootstocks must be collected from healthy and vigorous plants [68]. These researchers reported that pecan seeds exhibit dormancy, thus, they must go through a process to end it.

[69] evaluated the activity of scarification and stratification in seeds of the cultivar Barton at different storage periods up to sowing. Results showed that the highest emergence took place when both techniques were used and the material was stored for 90 days.

According to [40], the highest impact on the cost of a pecan tree orchard is the seedling. Therefore, careful selection of seedlings, which should be as uniform as possible, increases the chances of germination after they have been planted. In Brazil, nurseries yield covered-root seedlings (or wrapped-root seedlings) and bare-root seedlings. The former means that seeds are planted in plastic containers, at a depth of 2 cm, whereas the latter means that seeds are directly planted on beds, in open fields. After grafting, they are removed and sold with bare roots.

## 9. CULTIVATION SYSTEM

Ojeda-Barrios [44] reported that areas with potential to yield pecan trees are mainly located at latitudes south and north, between 25º and 35°. It encompasses the south and part of the southeast in Brazil.

The soil has to have good drainage and pH between 6 and 6.5. Above all, pecan trees require soils with effective depth and neither physical nor chemical constraints which favor radicular growth and development. Soils with high pH should be avoided since it hampers the availability of zinc, an important element for pecan trees [20].

Nitrogen is a macronutrient required by pecan trees. The Manure and Liming Manual of Rio Grande do Sul and Santa Catarina [70], which issues guidelines in southern Brazil, recommends at least three applications of this nutrient along the cycle.

Pecan trees also require much zinc [71]. In the USA, zinc is applied every 15 days to supply their needs [44]. In Brazil, some pecan tree farmers have carried out leaf application of zinc. Even though this practice is still poorly known, it has been used with no real knowledge of its need in Brazil.

Concerning spacing, it is recommended that pecan trees should be spaced 7 x 7m, even 15 x 15m, apart [49,72,73,74]. Spacing varies, depending on the cultivars, i. e., at least 10 m is recommended between the ones that yield late

(between 8 and 10 years) while less space is needed between the ones that produce earlier, since they need pruning to decrease shading. However, there are reports of dense orchards, whose trees are spaced 3 x 3m apart [75]. In this case, harvest is not feasible, mainly because pecan trees need a period to start producing. Besides, these orchards may not have had any technical assistance. Implementation can be carried out by positioning plants in square, rectangular, triangular and quincunx systems [20].

Precipitation required by the culture ranges between 760 and 2,010 mm. However, 200 plants per hectare are planted in orchards where precipitation is above 1,200 mm, whereas from 50 to 100 trees per hectare occupy areas where precipitation varies from 700 to 1,000 mm [11,26]. Precipitation is related to pecan quality, i. e., poor precipitation leads to disuniform filling of the nut and may even result in fruit abortion [76].

The ideal period to plant an orchard ranges from June to mid-August [74]. At least 4 cultivars are recommended to start a pecan tree orchard: one is the “producer” while the other three are pollinators [42]. [20] reports that an orchard has to comprise from 3 to 5 cultivars and that pollinators should represent 15% of the plants.

Depending on the climatic conditions of the area where the orchard is located, its density should be analyzed and an irrigation system may be needed, taking into account that drought may occur. In addition, in order to mitigate water loss from the soil, implementing forage crops is feasible to cover the soil in the orchard [26]. [77] studied the amount needed to irrigate regions located in Rio Grande do Sul state, from October to January, and concluded that it ranges from 13 to 262 mm.

Pruning is needed for commercial cultures of pecan trees. [78] reported that the following types of pruning can be carried out: shaping, production/fruiting, green, cleaning, thinning and renewal.

When pecan trees are adult and highly developed, shade can occur inside the crown and in the low branches of the plant, mainly in densely planted orchards. Shading causes reduced sunlight capture and shrinks photosynthesis activity [79]. As a way to prevent this effect, they must be pruned; it can be carried out by mechanical pruning, depending on the size of the plants.

In Brazil, this type of pruning has not been commonly used. Besides, pruning is rarely performed in adult plants, even because most Brazilian orchards are still young.

Pecan trees are characterized by alternation between large and small pecan production [26], whose variation depends on the cultivar, but management is important to mitigate this effect.

## 10. PECAN TREES IN CONSORTIA

Pecan trees are important species in an agroforestry system since they enable fruit and wood production, besides consortia with other cultures [40]. Benefits of the systems, mainly agroforestry ones, are the interaction and the synergism among biological components, which favor the subsistence of the system [80]. In Morro Redondo, RS, there is an agroforest which includes pecan trees. This species was chosen due to its rusticity and because spacing enables the use of other species between trees in the rows. It has been reported that small farmers in southwestern Paraná have used pecan trees in an agrosilvipastoral system.

In addition, according to the [72], initial low productivity of pecan trees in Brazilian conditions makes it essential to integrate them with other cultures so as to get some income. Another important factor is the time pecan trees need to start production, i. e., usually after the 5th year. Even so, production is very low and a complementary culture is needed.

There are reports of pecan tree orchards in consortia with corn, manioc, beans, soybeans, besides cattle and sheep [26]. A consortium with erva-mate (*Ilex paraguariensis*) is also feasible because the herb develops in a shaded area and may have its flavor and quality improved [26].

Yanagizawa [81] carried out a study of floristic composition in a pecan tree orchard in Botucatu, SP. Since pecan trees are deciduous, i. e., they shed all leaves in dormancy, sunlight penetration is favored and influences *Brachiaria decumbens* and *Panicum maximum* growth to form pasture. However, pecan trees must be observed in fruitpastoral systems because animals cannot be left in the area in the implementation phase, unless pecan tree seedlings are protected.

## 11. DISEASES AND PLAGUES

Some diseases of pecan trees in Brazil were described by [21]. They pointed out pecan scab, caused by the fungus *Venturia effusa* (synonyms: *Fusicladium effusum* G. Winter; *Cladosporium caryegenum; C. effusum; Fusicladium caryegenum*). This disease attacks young tissues, such as leaves, petioles, epicarp and catkins. The authors also stated that there was no scab in Brazil before the introduction of the cultivar Wichita, which contaminated the cultivar Mahan and led to decline in the pecan culture. Since the fungus can be harmful when it enters the orchard, it affects pecan yield. This is the main disease in Rio Grande do Sul state [36].

The ideal temperature for scab development in spring is between 20 and 25°C. In addition, high humidity along with excessive precipitation favors scab [58,82]. Humidity above 80% for more than two days in a row favors scab development [26].

Poletto et al.[18] and [20] recommended that the Bordeaux mixture should be applied to pecan trees in dormancy. According to [82], another important factor is that scab control is more efficient when the whole vegetative canopy is exposed to sunlight.

Anthracnosis, caused by *Glomerela cingulata*, the sexual phase of *Colletrotrichum gloesporioides*, occurs as depressed, round and dark lesions on fruits and results in decrease in nut size and fruit abscission which ends up detaching the epicarp from the nut shell [18].

In Rio Grande do Sul, [48] found *Fusarium* spp. in pecan tree flowers (female and male ones), roots and seeds. Their symptoms were wilt, trunk girdling, low growth and superbudding. Besides this fungus, *Pestalotiopsis* spp. was also found. It develops on leaves and causes leaf stains whose initial characteristic is spots that coalesce and seem to have been burned. When lesions evolve, they may cause partial loss of pecan tree leaves, leading to decrease in the photosynthetically active area and low yield. [83] carried out laboratory experiments in which they investigated 15 isolates of *Trichoderma* as the result of two isolates of *Pestalotiopsis clavispora*. Results showed that the 15 isolates had an antagonistic effect due to the pathogenic fungus. Besides, they collected *Trichoderma* on pecan tree leaves and found antagonistic efficiency to both isolates. Taking into account that there are no registered agrochemicals to control diseases and plagues in Brazil, these results show that the biological control can be used.

Poletto et al. [6] were the pioneer researchers that found canker caused by the fungus *Lasiodiplodia subglobosa*, which damages pecan tree trunks. The disease, which was found in Santa Maria, RS, is capable of causing 100% plant loss when the tree has the symptom, i. e., tree bark cracking. [18] carried out a study of pecan tree staminate and pistillate flowers and seeds. In pistillate flowers, they found high incidence of *Alternaria* sp. and *Fusarium* sp., besides *Aspergilus* sp., *Cladosporium* sp., *Curvularia* sp. and *Penicillium* sp.. Staminate flowers had high incidence of *Fusarium* sp.. Pecan tree seeds carried *Cephalosporium* sp., *Colletotrichum* sp., *Fusarium* sp., *Penicillium* sp. and *Verticillium* sp.

Certain diseases occur at the end of the crop and attack mostly fruits. *Aspergillus* sp. and *Penicillium* sp. cause mold and produce aflatoxin [50]. In their experimental evaluation, the authors found the fungi that cause scab and anthracnosis, besides *Rhizopus* sp. and bacteria, in treatments with and without asepsis. *Alternaria* sp. is another fungus that may harm seedlings by propagating through rootstock seeds [18].

Sooty mold (*Capnodium* sp.) is a disease connected to the blackmargined aphid (*Monellia caryella*) which attacks leaves, fruits and branches. It excretes a yellowish substance, where the fungus develops, and causes physical blockage of photosynthesis [18,83].

In Brazil, 18 pest species were recorded for walnut, highlighting the parasites that cause damage to leaves such as the *Monellia caryella* aphid and the phylloxera species *Phylloxera devastatrix* and *Phylloxera notabilis*. Besides these, leaf-cutting ants (*Atta* sp. e *Acromyrmex* sp.) are among the main leaf stripper pests Recently, damage was reported on fruits caused by phytophagous insects *Leptoglossus stigma*, *Leptoglossus zonatus* and *Loxa deducta* [84].

It is clear that sustainable cultivation of pecan trees is based on the improvement of agricultural practices and on the implementation of new cultivation methods, mainly related to soil and plant management that aim at decreasing losses caused by plagues and diseases. Incidence of diseases in orchards has become a factor that limits production as results of studies have shown the dimension of the problem. Even though there are no official data, production

losses due to disease attacks to cultures in the region are estimated to be about 50% [83]. Pecan trees must definitely be considered a culture with insufficient phytosanitary support (minor crops) because it does not have a defined group. The *Instrução Normativa Conjunta* (Joint Normative Instruction) no. 01, issued on June 16th, 2014, whose definition of culture grouping is similar to the one of Codex Alimentarius, also takes into account morphological aspects of cultivars produced in Brazil, their taxonomic proximity, similarity of agricultural practices and forms of consumption. Therefore, pecan trees have not been listed as cultures with insufficient phytosanitary support yet. They do not have any registration of agrochemicals, either. It is an enormous technical fragility that must be solved soon.

## 12. POST-HARVEST

The amount of nut in the pecan is an important feature, i. e., the larger, the better. Besides increasing yield and profit, it also has enough reserve for seedling production. In addition, traders and farmers prefer pecans with thin shells, since this fact makes processing and *in natura* consumption easier.

Regarding long storage periods, it is essential that fruits neither lie on the soil nor are exposed to climatic adversities. If pecans lie on the soil, they may lose their color and be infested by fungi [74].

When pecans are picked, their humidity rates range from 20 to 30%. Thus, they must undergo a drying process to reduce humidity to about 4% and preserve the nut [85].

Processing usually uses the initial washing process in cold water and then the one in warm water, Finally, pecans are ready for shelling [40].

Pecan storage at low humidity enables its commercialization in the off-season period, a fact that leads to better prices. [31] carried out a physicochemical and sensory analysis of pecans, whose shelf life was 120 days, stored in polypropylene containers and in vacuum nylon-polyethylene films. The sensory analysis showed that pecan oil storage for 60 days causes no sensory alterations.

## 13. COMMERCIALIZATION

Nowadays, Rio Grande do Sul cultivates pecans in areas that range from 1 to 300 ha. [48] reports yields of 30 kg per tree. In Argentina, [54] calculated yields in agreement with the ages of pecan trees (12 x 12m spacing; density of 70 trees/ha), as shown in Table 3. [49] estimated yields of pecan trees which were 5, 7 and 10 years old and found low values for 5 and 10-year-old plants. The highest discrepancy was found in 10-year-old plants, i. e., this author found 11.7 kg per plant, about half the value reported in Argentina. In 2015, Emater-RS carried out a study in Anta Gorda, RS, where 1 kg was yielded per plant in the 5th year and the double was picked in the following year [86]. In the 10th year, yield was 18 kg per plant. It is below the value reported in Argentina but close to the minimum value that was established.

**Table 3. Year of pecan tree and yield per area and plant in Argentina**

| Year of tree | Yield (kg/ha) | Yield per plant (kg) |
|---|---|---|
| 5th to 6th | 70 to 140 | 1 to 2 |
| 10$^{th}$ | 900 to 1,000 | 20 to 24 |
| 20th to 25th | 2.000 to 2,500 | 35 to 40 |

*[1]By [54]*

Productivity of this standard is related to adult plants. However, the production cycle of pecan trees may live 100 years [22], a fact that compensates the initial investment. Besides, there are reports of trees that lived 200 years [30,49].

Farmers have invested in the pecan tree culture lately, mainly because of the valuation of prices paid for pecans. According to [83], it is one of the most profitable cultures per area in Rio Grande do Sul state. However, current prices range from R$10.00 to R$12.00/kg with shells. In the off-season period, prices tend to rise.

In Brazil, besides pecan (nut) commercialization, processing of the whole nut, pieces, fine and coarse flour is carried out. Pecan oil is also extracted.

An alternative income source is the pecan shell which is consumed as tea and can also be used as substrate. [87] studied this residue and found physical and chemical properties of the pure substrate and mixed with peat. Besides, the authors reported that a company had generated 150,000 kg/year of pecan shell in 2007. It costs R$ 0.50/kg and represents another option of income.

Filipin [40] conducted a study of the economic feasibility of pecan trees in western SC, in legal reserve and permanent preservation areas. He succeeded in exploring the culture in these areas and introduced them as alternative income sources. In a legal reserve area, an orchard with 204 plants has had positive financial results in its 7th year. However, the author estimates that plants should yield in the 3rd year (production is low at this age, i. e., about 200 g/plant). In a permanent preservation area, 40 plants were implemented and had positive results in the 8th year. Economic indicators were feasible in both areas.

Another issue that may provide profit is the possibility of selling the wood, even though this market has not been developed in Brazil yet. [88] reported good bend radius, i. e., it is a species that may be used for building furniture. Wood may result from the thinning process and from old orchards, mainly from trees which were non-grafted seedlings.

Finally, pecan trees may also be used as ornamental species and in derivative industries, such as dye extraction in tanning. [54].

## 14. CHALLENGES AND PERSPECTIVES OF PECAN TREES (CONCLUSION)

The pecan tree culture has been expanding in South Africa, Australia, Argentina, Uruguay and Brazil. In Brazil, a significant percentage of older orchards is based on trees which originate from seeds, but new areas have been prepared with selected varieties.

The development of new orchards along with the existing ones has placed Brazil as a potential supplier of this product worldwide, since, in the future, there may be a larger gap between supply and demand. Therefore, Brazil may be considered a supplier of pecans in the short and in the medium terms. There is also enormous and potential internal consumption in Brazil.

So far, it may be observed that productivity (high yields and high quality) of orchards in general has been below their potential. Even though causes that generate this difference between the current situation and the potential very much, the most important factor which shows significant deficit is lack of reliable technical information, i. e., scientific knowledge, mainly concerning solutions for phytosanitary problems that affect productivity and product quality.

Therefore, solving obstacles related to production and improving orchard productivity may lead to great opportunities to supply the Brazilian market and increase participation in external markets.

Therefore, the following crucial issues are challenges and opportunities that research institutions should face:

1. Systematization of nutritional, regional phytosanitary and variety factors that limit productive potentiality and culture expansion;
2. Acknowledgement of the pecan tree culture as one with insufficient phytosanitary support and its appropriate grouping. It does not have any registration of agrochemicals, an enormous technical fragility that must be immediately solved;
3. Determination of the edafoclimatic zoning for pecan trees so as to consolidate and expand the culture in southern Brazil;
4. Identification of ecological cultural practices of soil and water management to provide better plant development along with rational use of natural resources;
5. Identification of phytosanitary problems and ecologically adequate strategies to live with and manage insect-plagues and pathogens in pecan tree cultures, in compliance with principles of ecological intensification;
6. Development of input (fertilizers and phytoprotectors) to be used in production systems.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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