Lycopersicon esculentum 'Indigo Rose': A new horizon in tomato farming

https://doi.org/10.56238/sevened2024.023-009

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ABSTRACT
The tomato variety *Lycopersicon esculentum* 'Indigo Rose', recognized for its distinctive purple coloration and high anthocyanin content. Developed to improve disease resistance and increase nutritional benefits, this tomato variety stands out for both its aesthetics and its health benefits.
In this context, the present study aimed to address the botanical and genetic characteristics of 'Indigo Rose', which led to its creation. Agronomic aspects are presented, including recommendations on cultivation practices, from soil preparation to harvesting. Resistance to pests and diseases, along with adaptability to different climatic conditions, is highlighted as a key factor for success in growing this variety.
The nutritional benefits of 'Indigo Rose' are widely discussed, with an emphasis on anthocyanins and their antioxidant effects, furthermore, it presents the economic and market impact of this variety, underscoring the growing demand for functional and visually appealing foods among health-conscious consumers.

Keywords: Pink indigo tomato, Nutritional composition of pink indigo, Botanical characteristics, Market prospecting Modified tomato.

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INTRODUCTION

Tomato farming has a long history, rooted in farming practices that date back thousands of years. Within this vast field of study and cultivation, *Lycopersicon esculentum 'Indigo Rose'* stands out as a particularly interesting strain. This chapter aims to explore the unique characteristics, genetics, and nutritional benefits of this peculiarly colored tomato, bioactive compounds, agricultural activities, toxicological safety, and market (Balashova; Pinchuk, 2019).

The 'Indigo Rose' variety is notable not only for its deep purple coloration, but also for the bioactive compounds that give it this hue. Developed through selective crossbreeding, this strain was created to improve resistance to diseases and increase the content of anthocyanins, powerful antioxidants beneficial to human health. Anthocyanins are responsible for the characteristic coloration and have been associated with reduced risk of cardiovascular disease, diabetes, and certain cancers (He et al., 2023).

In addition to the nutritional aspects, 'Indigo Rose' has a number of agronomic characteristics that make it attractive to growers. Its resistance to pests and diseases, coupled with its ability to adapt to different climatic conditions, makes it a robust choice for sustainable agriculture, its way of cultivation, and the economic and market impacts of 'Indigo Rose' (Zhi et al., 2020).

'Indigo Rose' is not only a functional food but also an attractive aesthetic option for chefs and consumers who value the visual appearance of the food they consume (Vu et al., 2019).

By exploring the *Lycopersicon esculentum* 'Indigo Rose', the present work aims to provide a holistic understanding of its potential and challenges, highlighting its contribution to modern agriculture and human nutrition.

BOTANICAL CHARACTERISTICS

The tomato (*Solanum lycopersicum*) belongs to the order Tubiflorae and is a member of the *Solanaceae family*, being a Dicotyledonous plant (Maureira et al., 2022). It stands out among the most cultivated vegetables in the world, due to its high nutritional content and economic potential (Perez-Robles et al., 2023).

The tomato (*S. lycopersicum*) is one of the most appreciated vegetables in the world due to its flavor and its wide variety of shapes and colors. It is a widely cultivated and used vegetable, due to its versatile characteristics, it can be consumed fresh, cooked, or processed (Amr, 2022). Tomatoes are a rich source of functional compounds, ranging from vitamins, minerals, dietary fiber, proteins, and essential amino acids such as carotenoids, chlorophylls, and polyphenols (De Corato, 2020).

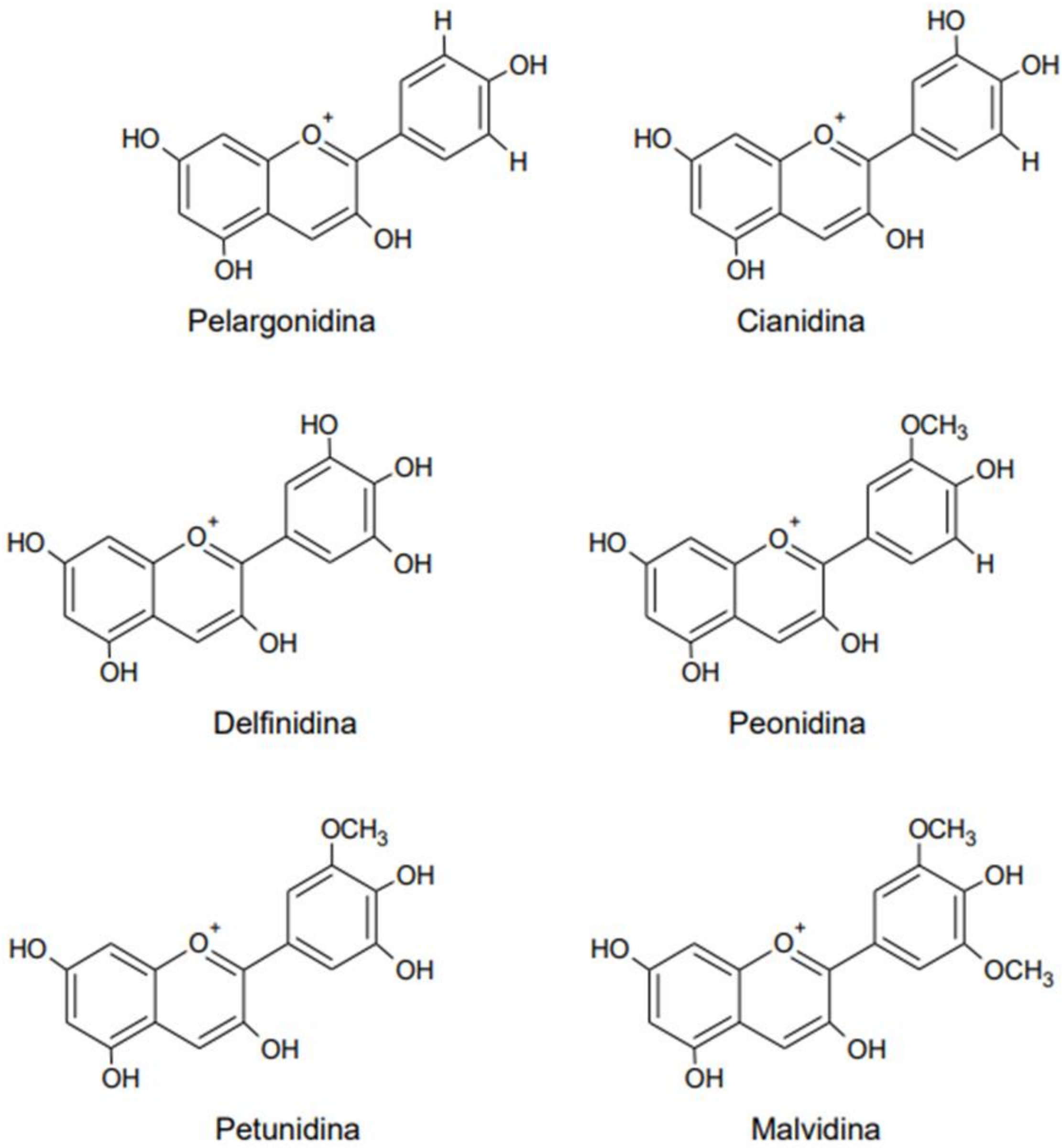
The tomato plant has different genetic varieties, allowing the selection of genotypes that are better adapted to the region of interest and that efficiently reproduce its genetic potential. And this directly interferes with the quality of the fruit, such as soluble solids content, titratable acidity, pH, vitamin C, fruit mass and size, among other traits, is fundamental in the choice of superior genotypes (Mohamed et al., 2012).

In recent years, the tomato cultivar 'Indigo Rose' has gained attention due to its purple-skinned fruits being rich in anthocyanins with antioxidant action (Kang et al., 2018). Indigo Rose was created from wild tomato species through gene transfer from the anthocyanin fruit (Aft gene) of *Solanum chilense* and the locus atroviolacium (Atv gene) of *Solanum cheesmaniae* in cultivated tomatoes (Mes et al., 2008).

The genetic variability linked to the pigments of the tomato fruit has allowed the diversification of the fruit composition and eventually properties related to its nutritional value. The tomato fruit is a berry that can take on different shapes and colors. The color of the fruit progressively changes from green to yellow, orange, and red, when different carotenoids and flavonoids are synthesized, and lycopene, the main carotenoid in ripe red fruits, is finally accumulated. Tomatoes are climacteric fruits, and the production of high levels of ethylene is observed early in their ripening (Naeem et al., 2023; Amr, 2022).

Tomato fruits are rich in pigments such as lycopene and carotenoids, but they contain only small amounts of other flavonoids. Anthocyanins, in turn, are an important class of flavonoids that represent a large group of secondary metabolites in plants. Anthocyanins are composed of glycosylated polyphenolics with a range of colors ranging from orange, red, and purple to blue in flowers, seeds, fruits, and vegetative tissues, among the most common we have pelargonidin, cyanidin, delphinidin, peonidin, petunidin, and malvidin (Fig. 1), they can be synthesized, differing in the substituent groups in the structural rings (Cappellini et al., 2021). Anthocyanins are known for their health-protective function in a daily diet, as they are able to activate antioxidant defenses. Therefore, strategies such as genetic engineering and breeding programs have recently been carried out to increase the anthocyanin content in tomatoes (Gonzali & Perata, 2021).

Figure 1: Structure of the main known anthocyanins.



Source: ChemSketch elaborated.

The Aft gene encodes an R2R3 MYB transcription factor called AN2-like, which upregulates anthocyanin biosynthesis in a light-dependent manner (Sun et al., 2020). Thus, the dominant allele of the Atv gene encodes an R3 repressor MYB MYBATV that downregulates anthocyanin biosynthesis, while the recessive Atv allele in Indigo Rose encodes a non-functional version. In the case of Indigo Rose tomatoes, the anthocyanin content is mainly restricted to the skins (Yan et al, 2020; Liu et al., 2020). Thus, the Indigo Rose tomato cultivar is relatively new to the tomato plantation (Teo et al., 2022).

ANTHOCYANIN CONCENTRATION AND COMPOSITION OF INDIGO ROSE TOMATOES

Anthocyanins are natural pigments with diverse physiological functions and protective effects, but most tomatoes produce little anthocyanins (Jian et al. 2023). Solanaceous fruit vegetables, which mainly include tomatoes (S. lycopersicum), exhibit natural variations of anthocyanin pigments in terms of specific tissue types, contents, and patterns. Breeding anthocyanin-rich varieties is the predominant avenue to improve the quality of this vegetable, as anthocyanin-enriched tomatoes have been obtained employing breeding or transgenic approaches (Li et al., 2022; Teo et al. 2022).

Anthocyanins in the tomato fruit (*S. lycopersicum*) are biosynthesized in a light-dependent manner. It can be found in the form of nine structures of anthocyanins, such as petunidine-3-(trans - p -cumaroyl)-rutinoside-5-glycoside, which is the main anthocyanin present in tomato, (delfinidine-3-(caffeoil)-rutinoside-5-glycoside, delfinidine-3-(trans -cumaroyl)-rutinoside-5-glycoside, delfinidine-3-(feruloyl)-rutinoside-5-glycoside, petunidin-3-(trans -cumaroyl)-rutinoside-5-glycoside, petunidin-3-(feruloyl)-rutinoside-5-glycoside, malvidin-3-(p-cumaroyl)-rutinoside-5-glycoside, malvidin-3-(feruloyl)-rutinoside-5-glycoside, petunidin-3-(caffeoil)-rutinoside-5-glycoside and delfinidine 3-(caffeoil)-rutinoside-5-glycoside (Wang et al. 2020)

The anthocyanins in Indigo Rose tomatoes, which are responsible for their purple and black color, have additional health benefits beyond those normally associated with tomatoes, such as antioxidant action and support cardiovascular health. The anthocyanin content in Indigo Rose fruits is mostly restricted to the skins of their fruits. Through the studies carried out by Teo et al. (2022), the author points out that the accumulation of anthocyanin occurred mainly in the peels of the fruits instead of the pulp, regardless of the stage of development or the growth conditions of the fruit. Since the fruit skin only accounts for about 5% of the total fruit mass, the total anthocyanin content is about 300 µg per g of fresh weight (Liu et al. 2020).

However, Mes et al., (2008) point out that the fruit loci genes anthocyanin (Aft) and atroviolacea (atv), are responsible for conditioning the intense purple color in tomatoes, in which the concentration of anthocyanin in the skin of their fruits reached more than 100mg per 100g of fresh fruit. Furthermore, (Liu et al. (2020) further revealed that Aft cooperates with Atv to form a feedback loop to adjust anthocyanin biosynthesis.

Using a mass chromatogram and ultraviolet (UV) absorption, Wang et al. (2020) analyzed the anthocyanins present in the skin and pulp of the Indigo Rose fruit, where they were able to identify 12 anthocyanin structures. Based on the structure, the author identified that petunidin-3-(trans-p-coumaroyl)-rutinoside-5-glucoside is the main anthocyanin in the peel of fruits. The total anthocyanin content present in the peel was higher than the anthocyanin concentration in the pulp, reaching 3977.93 mg/kg in the peel and 88.44 mg/kg in the pulp. These results indicate that anthocyanins are enriched in the bark of Indigo rose. Petunidin-3-(trans-p-coumaroyl)-rutinoside-5-glucoside and malvidin-3-(trans-p-coumaroyl)-rutinoside-5-glucoside were the two main anthocyanins in the peel, making up approximately 68.7% and 14.2% of the total anthocyanin content, respectively. In the future, tomatoes could be developed as a pharmacological source of antioxidant compounds through anthocyanin improvement, as well as being one of the most popular fruits in the world.

Organic acids are important components that strongly affect the taste and nutritional value of fruits. A total of six organic acids (citric acid, quininic acid, malic acid, tartaric acid, fumaric acid, and oxalic acid) have been reported to have been identified in tomato fruit (Jian et al. 2023). The content and composition of sugars play important roles in assessing the nutritional value of fruits, as they are largely responsible for their sweetness and flavor. Jian et al. (2023) obtained fructose, glucose, and sucrose results in tomatoes ranging from 4.67–9.50 $mg.g^{-1}$, 3.59–8.30 $mg.g^{-1}$, and 0.68–1.90 $mg.g^{-1}$, respectively. The fructose and glucose content in both the purple tomato showed a gradual increasing trend as the fruit matured, while the sucrose content decreased.

Finally, it can be said that the nutritional composition of the Indigo rose tomato is similar to the traditional tomato, and may present small variations due to factors such as growing conditions and specific cultivars. Indigo Rose tomatoes contain essential vitamins and minerals, including vitamin C, vitamin A, vitamin K, potassium, and folate. These nutrients play crucial roles in immune function, vision, blood clotting, and overall well-being.

CULTIVO E MANEJO *L. ESCULENTUM* 'INDIGO ROSE'

During tomato cultivation, it is necessary to carry out soil preparation, including the stages of liming and fertilization, choice of variety and crop during development and growth. In this way, the tomato crop ends up adapting to different types of soil, from acidic, sandy, heavy and slightly alkaline soils (Peixoto et al., 2017).

Some factors can contribute to low yield during tomato cultivation, such as planting in unfavorable seasons, low quality seeds, irrigation and fertilization problems, injuries and indirects caused by pests and diseases, and inadequate water with the amount of dissolved salts in the production market. In this way, they seek tools that are essential for minimizing adverse effects on the climate, increasing the quality of the raw material and in a sustainable way (Silva et al., 2020). soil (Pereira et al., 2020).

The tomato is considered a species widely used in genetic research, regarding the development of fruits resistant to diseases. Modern genetics and genetic improvement methods have not only contributed to the understanding of the genetic control of agronomic traits, but also contribute to the development of thousands of new cultivars (Lamichhane, Thapa, 2022). The main objectives of tomato breeding are high productivity, tolerance to biotic and abiotic stresses, capable of ensuring the management of genetic resources and their diversity (Celik, et al., 2023).

This Indigo Rose tomato cultivar was developed by Oregon State University (USA), where many biotechnological strategies were explored, leading to significant enrichment in lycopene, anthocyanins, and other flavonoids (Teo et al., 2022; Bassolino et al., 2022).

The breeding or engineering of tomatoes with a high anthocyanin content has aroused great interest, as the antioxidant capacity in purple tomato fruits is higher than in common tomatoes (Lu et al., 2021). The healthy properties of anthocyanin-enriched tomatoes, may be based on the ability to act as scavengers of reactive chemical species and inhibitors of cancer cell proliferation, results have been demonstrated in in vitro and in vivo studies, potential health benefits in humans (Gonzali & Perata, 2020).

In this way, the introduction of 'Indigo Rose' to the market reflects a growing trend in agriculture and consumption, where there is a search for foods that not only satisfy basic nutritional needs, but also offer additional health benefits. This cultivar not only contributes to the diversification of products available on the market, but also exemplifies the role of biotechnology and genetic improvement in promoting sustainable agricultural practices and improving the nutritional quality of food. Thus, the 'Indigo Rose' tomato cultivar represents a significant step forward in the advancement of agricultural science and in responding to the demands of consumers who are increasingly aware of the nutritional impacts of food.

TOXICOLOGICAL SAFETY ASPECTS OF MODIFIED CROPS ASSOCIATED WITH THE USE OF PESTICIDES

There are many questions under debate about the robustness of the data and methodologies used in GM (Genetically Modified) crops, and the 'Indigo Rose' fruit fits into this classification (Gilbert, N. 2013), and future studies are needed to better clarify these questions. Concerns about biodiversity and pest resistance also need to be clarified (Klümperç Qaim, 2014), since there is a dependence on patented seeds, which cause concern regarding food security. (Stone, 2012).

The genetically modified (GM) seed industry has faced several problems related to human health and insect resistance, in addition to inadequate communication by seed companies, the lack of comprehensive studies on safety in relation to (GM) have contributed to the amplification of these issues (Raman R, 2017).

The concern about GM foods revolves around the possibility that they may have harmful effects on human health. There are fears that the consumption of these genetically modified foods could contribute to the emergence of antibiotic-resistant diseases. In addition, as these are relatively new products, there is still significant uncertainty about their long-term effects on the human body

(Bawa; Anilakumar, 2013). The health risks associated with genetically modified foods involve toxins, allergens, and genetic risks.

Consumer acceptance is influenced by the perceived risk of incorporating processed foods with technologies they understand little about. A study conducted in Spain showed that the introduction of GM foods into agri-food markets must be accompanied by appropriate policies to ensure consumer protection (Martinez et al., 2009). Within this context, the purple tomato of the 'indigo Rose' type *S. lycopersicum* was an alternative strategy to develop anthocyanin-rich tomatoes using genetic improvement, taking advantage of wild species of *Solanum* that produce anthocyanins under appropriate conditions (Gonzali; Mazzucato; Perata, 2009). However, studies on toxicological aspects are not reported in the literature for the purple tomato species.

TECHNOLOGICAL PROSPECTING AND FUTURE MARKET PROSPECTS

A patent study was conducted in July 2024 on the Espacenet database to analyze the market and future prospects for *L. esculentum* 'Indigo Rose'.

Espacenet is the database of the European Patent Office (EPO), which provides free online access to millions of invention patent documents and technical developments from around the world. The monitoring of patent data is done in different ways (e.g., bibliographic data, reproduction images, and full text), ensuring accurate and up-to-date information. Espacenet also provides documents filed with the National Institute of Industrial Property (INPI) and in several American offices. (EPO, 2023a).

The patents filed were collected by combining the keywords "Lycopersicon esculentum Indigo Rose" in the advanced search field. No specific time frame was made for the search, so that more documents could be obtained and also to observe its annual evolution in general regarding deposits.

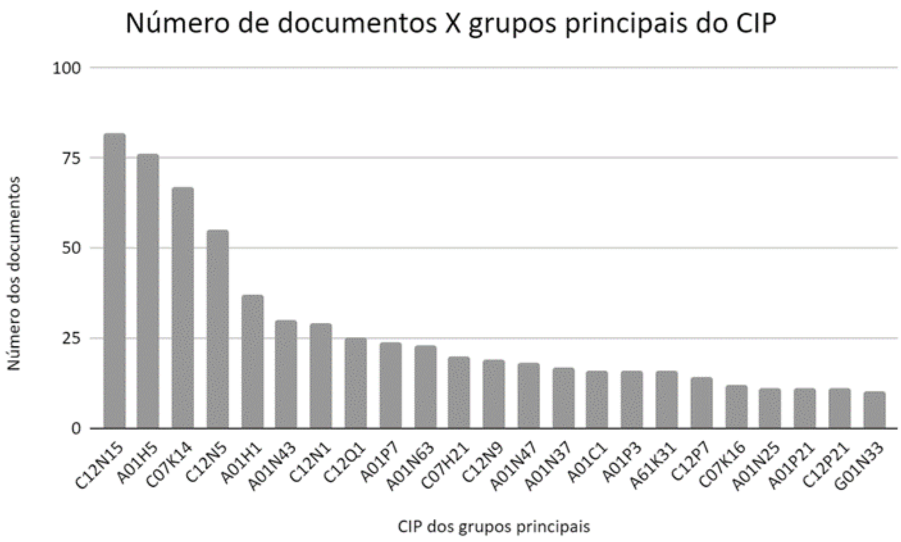
After performing the word search as described above, 604 publications were found that meet the keywords, of which 147 were available for access. The documents available for analysis were exported to the Microsoft Office Excel program, with the objective of analyzing the patent information and generating the images that we will see in this study.

The main International Patent Codes (CIP) found in the research are illustrated below (Figure 2). Among them is the code C12N15/00, which refers to "mutation or genetic engineering; DNA or RNA relating to genetic engineering, vectors, and plasmids, or their isolation, preparation or purification; use of hosts for them (mutants or genetically modified microorganisms)", which is consistent with the fact that the plant researched is the result of genetic engineering.

The second most cited code was CIPA01HS, which names the class described as "angiosperms, that is, flowering plants, characterized by their plant parts; angiosperms characterized in a way other than by their botanical taxonomy", which is also related to the plant in question.

After analyzing the other CIPs described in the figure, we can say that most of the main codes found are related to the areas of Chemistry and Agriculture, which is expected, since we are searching for a vegetable, and, therefore, fits into both areas.

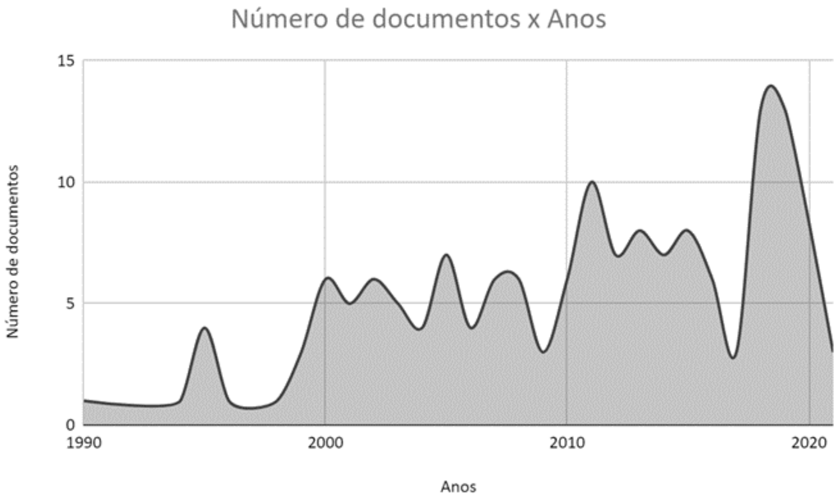
Figure 2. Main patents filed, broken down by International Classification Code.



Source: prepared with data from EPO (2024b).

The annual evolution of the filing of patent documents shows that the first registration was carried out by the University of North Carolina, in the United States, and filed in 1993, with registration number CA2112999A1 and entitled "Transgenic plants resistant to pathogens" and describes characteristics of certain plants with genetically modified genes, which become more resistant.

Figure 3. Annual evolution of patent documents filed in the period between 1995 and 2021.



Source: prepared with data from EPO (2024b).

It was observed in Figure 3 that from the year 2000 onwards, there was a trend of increase in the number of patents filed, however, it was from 2011 onwards that, in fact, there was an increasingly progressive increase in the filing of documents referring to *L. esculentum* 'Indigo Rose'. The years 2018 and 2019 had the highest number of filings (13). Few patents were filed in 2021, which can be explained by the period of secrecy, after the filing of these patents, until they can be available for public consultation. Three patents were published in 2021: one from the United States (US2023270073A1), and two with the registration codes WO2023230428A1 and WO2023152723A1.

The letters "WO" show that the patent was published by the World Intellectual Property Organization (WIPO), in compliance with the Patent Cooperation Treaty (PCT). The PCT is an international agreement that favors the protection of inventions through patents in several countries. Patents registered using the PCT have their acronym beginning with WO.

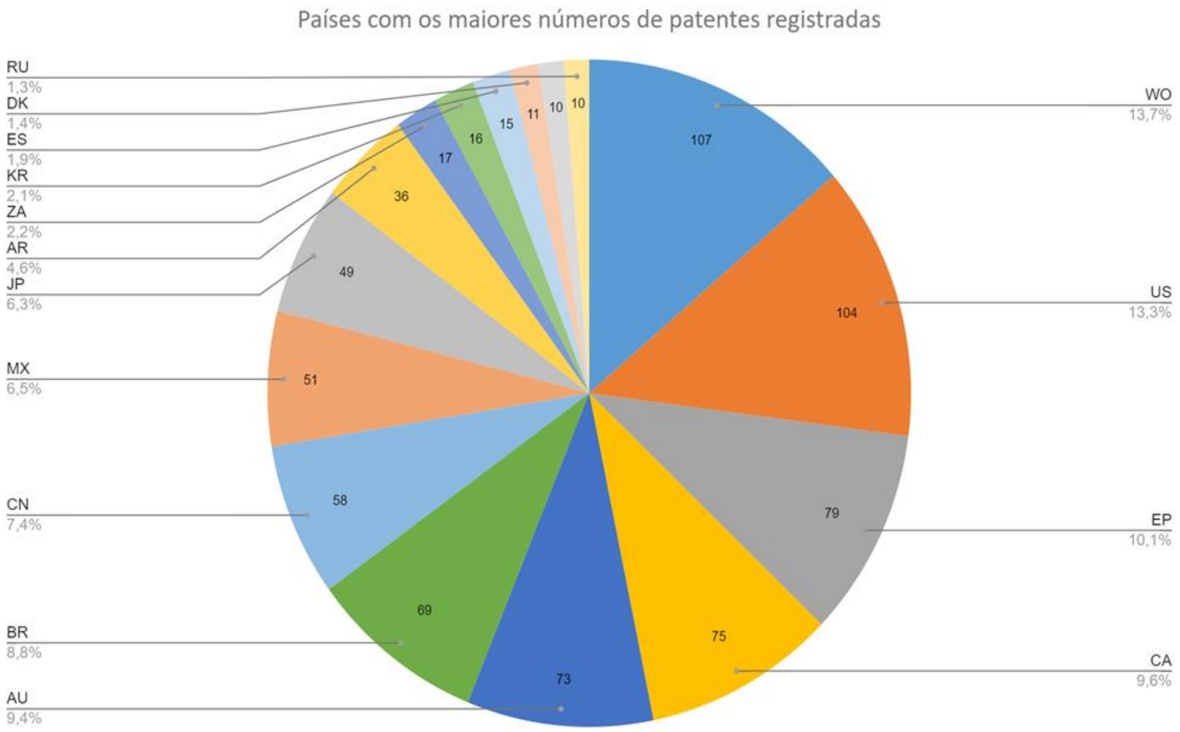
Among the main patent applicants, those published by the WO are the ones with the highest number, with 107 (13.7%) deposits on *L. esculentum* 'Indigo Rose', as shown in Figure 3. The acronym WO represents that the registration is at an international stage and indicates an international publication within the scope of the PCT, which allows the inventor to seek patent protection in different countries using a single application.

Soon after, the second largest applicant is the United States (13.3%), followed by the European Patent Organization (10.1%), followed by Canada (9.6%), followed by Australia (9.4%) and also by Brazil (8.8%). It is also noted the presence of countries such as China, Mexico, Japan, Argentina, South Africa, the Republic of Korea, Spain, Denmark and Russia, which shows, in general, that the interest in the plant is global and independent of the level of social development of the countries.

One of the most consumed vegetables in the world is tomatoes, with an average annual consumption of 20.9 kg per person, reaching more than 50 kg per person in some Mediterranean countries. The world's largest producer is China, but the largest exporter is Mexico (FAO, 2020). In recent decades, tomatoes have shown a continuous increase in productivity and also in global production, expanding their importance in human food (Fernie and Yan, 2019).

Figure 3 represents the patent registrations made by the main applicant countries, which are those that have more than 10 registrations on the subject and among them we can verify the presence of the largest producer and exporter of tomatoes, which is consistent with the interest of these regions in the subject.

Figure 4. Main applicants of patents on *L. esculentum* 'Indigo Rose': WO, World Intellectual Property Organization; US, United States of America; EP, European Patent Organization; CA, Canada; AU, Australia; BR, Brazil; CN, China; MX, Mexico; JP, Japan; AR, Argentina; ZA, South Africa; KR, Republic of Korea; ES, Spain; DK, Denmark and UK, Russia.



Source: prepared with data from EPO (2023b).

The technological prospecting studied shows that the number of patents on the subject has been increasing in recent years, which demonstrates an interest in the subject. According to the FAO report, the global market for tomatoes, as well as other agricultural products, faces several challenges. Projections for the next decade indicate a continued growth in global agricultural production, driven by the advance of plant breeding, such as *L. esculentum* 'Indigo Rose', and the transition to more intensive production systems.

CONCLUSION

Through research, we have discovered that L. *esculentum* 'Indigo Rose' has important and essential components for health with emphasis on the importance of the anthocyanins present, which not only give a vibrant purple color, but also offer antioxidant properties that contribute to health promotion. These compounds have been linked to reduced risk of various diseases, making 'Indigo Rose' a nutritionally rich and valuable option.

Its combination of health benefits, ease of cultivation, and visual appeal suggests a promising future. This variety is expected to continue to gain popularity, contributing to more sustainable agriculture and a healthier diet for consumers worldwide.

THANKS

The authors thank the National Council for Scientific and Technological Development - CNPQ.

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