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Development of hop cultivation in new growing areas: The state of the art and the way forward

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ABSTRACT

The recent exponential growth of craft beer sector led many brewers to seeking strategies to differentiate their beers from other similar products. For emerging hop-producing countries, one of these strategies relied on the use of local hops, thus taking advantage of the "terroir" effect. This market trend has increased the demand for raw materials from breweries, with positive effects on agricultural production, including hops. However, lack of knowledge along all the hop supply chain heavily hinders the development of a steady and efficient hop production. Particularly, growers urgently need information about the best agronomic practices, which should be adopted to achieve a sustainable hop production, under both conventional and organic farming. Unfortunately, studies on basic hop farming are scarce and often inadequate. The aim of this review is to analyze what agronomic research has done working on hops in the new growing areas (e.g., Brazil, Florida, France, Italy and Virginia) and what it has still to do to facilitate the hop growers in building and conducting their own hopyard. Through this analysis, we also aimed to provide directions for policymakers and scientific community that want to develop a hop supply chain starting from its basis. The review highlighted that while the screening of existing hop commercial cultivars was adequately referenced, the agronomic practices and growing technics suited for each new growing zone are still little studied or completely unknown. The use of artificial LED lighting is a key theme at the lowest latitudes of Florida and Brazil, organic management is pivotal in Italy and France, while alternative trellis design and hop breeding plans represent the shared research interest in all the emerging hop growing zones.

1. New frontiers of hop cultivation

The promotion of a healthier lifestyle, especially in higher-income societies, has caused a shift to a greater consumption of low-alcohol beverages. Craft brewing revolution, started in the U.S.A. and rapidly spread all over the world, anticipated this trend and, somehow, favoured its development (Anderson, 2023). A craft brewery is defined by several key criteria, which can differ according to national laws. Overall, these regulations distinguish craft breweries from larger industrial breweries by focusing on production volume (small), ownership (independent), and brewing methods (traditional and using high-quality and natural ingredients). The annual production limit can significantly vary among countries. For example, in Brazil it must not exceed 5 million liters, in Italy and France this limit is 20 million liters, while in the U.S.A. it reaches 704 million liters. At the base of this revolution is a new concept of hops in the brewing process: from a simple agent of bitterness to the key ingredient for distinctiveness of beer (Legun et al., 2022). Recently, the sensory attributes of beer were related not only to the genetic factor (the use of different aroma hop varieties) but also to the "terroir" effect (Van Holle et al., 2021). All these novelties kicked off an exciting period in the beer industry, thus encouraging many brewers around the world to grow their own hops and, therefore, their own beer. The exploration

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Fig. 1. Geography of the cultivated hop. Blue icons: large and/or traditional growing areas; Red icons: small and/or new growing areas (made by using Google My Maps).

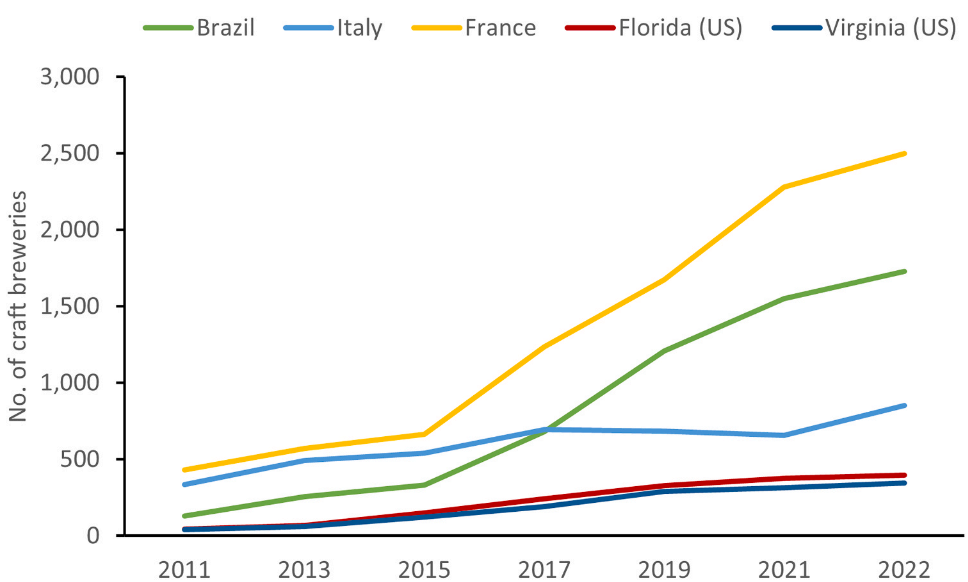

Fig. 2. Number of craft breweries in Brazil, Italy, France, Florida (US) and Virginia (US) from 2011 to 2022. Sources: Mapa - Ministério da Agricultura e Pecuária, (2024); Brewers Association (http://brewersassociation.org); Bimbo et al., (2023); Gasparini, (2024); Gillard, (2023).

of suitable pedo-climatic conditions for hops, out of their traditional growing areas, is the evidence of a clear interest, especially of a part of the brewing sector (craft breweries, agricultural breweries, pub brewhouses etc.), in finding its own way in the premiumization strategy (Anderson, 2023; Rossini et al., 2021).

The largest part of commercial hop is traditionally grown in some areas between 45° and 52° north of the equator (Fig. 1). Specifically, Germany has four main hop-growing regions (Hallertau, Elbe-Saale, Tettnang, and Spalt), the U.S.A. produce nearly all their hops in three States of the Pacific Northwest (Washington, Oregon and Idaho), three are also the hop regions in the Czech Republic (Žatec, Tršice and Úštěk), one is in southwest Poland and one in Slovenia (Savinja Valley). These five countries handle 86 % and 85 % of the global hop acreage and production, respectively (IHGC, 2023). Out of America and Europe, China is the biggest producing country, accounting for about 4 % and 5 % global acreage and production, respectively (IHGC, 2023).

The search for new hop growing areas is currently underway in the U.S.A. (Acosta-Rangel et al., 2021; Rutto et al., 2021) and Brazil

(Fagherazzi et al., 2023; Fortuna et al., 2023; Jastrombek et al., 2022; Leles et al., 2023) as well as in Italy and France (Loussert, 2023; Ruggeri et al., 2023a) (Fig. 1). The recent success of the craft beer sector in these new growing areas is shown in Fig. 2. Other countries, such as Russian Federation, are trying to restore and innovate the hop cultivation system after a long period of dramatic decline (Khlynovskiy et al., 2023; Malinina et al., 2021).

Generally, all these pioneer hop growers are located at low latitudes (if compared to those of traditional growing areas) and share the same issues in creating an efficient hop supply-chain. The first step toward the introduction of a new crop is to understand: i) whether the existing commercial cultivars (often selected in a completely different environment) adapt well to the local pedoclimatic conditions and ii) which of them perform better for both yield and quality aspects. The second action is the optimization of the management practices to obtain a suitable and sustainable product for the new cultivation area and stakeholders needs. In other words, the first and often main obstacle a hop grower finds in a new growing area is the fine-tuning of agronomic practices for that location.

The aim of this review is to analyze what agronomic research has done working on hops in emerging growing areas of Italy, Brazil, France and U.S.A. and what it has still to do to facilitate the hop growers in building and conducting their own hopyard. Through this analysis, directions for policymakers and scientific community, interested to develop the hop supply chain starting from its basis, come also out.

2. The national hops: a bitter long way

2.1. Italy

In Italy, the national beer sector has been experiencing a decade of uninterrupted success, with the production of 1.7 billion liters (L) in 2023 and an annual revenue of more than 10 billion €. Annual imports (0.74 billion L) were mainly from Germany (42 %) and Belgium (21 %), while exports (0.36 billion L) were principally to United Kingdom, Albania and France. However, self-sufficiency for raw materials is still far from being achieved. As for hops, imports (as powder and extract), primarily from Germany and France, reached 5425 tons in 2023 (Assobirra, 2023).

Although Italy is considered a new growing area for the cultivated hop, attempts to introduce this crop in the country date back to the XIX century. Around 1830, Mr. Pietro Soresi, an agronomist, imported about 2000 hop rhizomes from Bavaria, planted them in his farm near Milan and, in this way, he originated probably the first hopyard in the history of Italy (Tagliabue, 1836). From that period to the beginning of the XX century, other sources attest the presence of hop gardens in northern and central Italy, especially in valley floor areas, which were not suitable for grapevine cultivation. At that time, many Italian brewers still used wild hops, which naturally thrived along all the Italian Peninsula, picking them from hedgerows and riverbanks. However, the quality of beers made using those cones was extremely low as compared to that of selected varieties. Despite the encouraging experiences of the hops' pioneers, the cultivated hop was not able to succeed in the land of wine and no other noticeable information we had about hops for about 70 years. In the late eighties, a renewed interest in hop cultivation was testified by studies which aimed to explore the acclimation and the agronomic performances of different commercial varieties in some locations of northern and central Italy (Biancardi and Wagner, 1989; D'Antuono et al., 1989). These papers represent the first scientific reports on hop cultivation published in Italy. However, the promising results obtained for yield and quality aspects were not sufficient to make hop a common crop across Italian countryside. Finally, after more than 20 years of additional oblivion, the topic of "national hop" had a sudden revival in the frame of the Italian craft brewing revolution (Fastigi and Cavanaugh, 2017), attracting an increasing attention of scientific community. After almost 200 years from the first attempt to introduce the cultivation of hops, this plant remains largely unknown among the Italian farmers and Italy continues to be a new growing region. However, thanks to the increasing consumption of beer at the expense of wine, especially in the youngest people (Istat, 2024) the presence of small/medium hopyards in Italy has never been so widespread as today. According to the official statistics (CREA, 2020), in 2020 some 52 ha were recorded in 109 hop-cultivating farms in Italy. A large amount of these farms (almost 57 %), sharing 67 % of the total hop cultivated area, were in the North, 35 % in the central part of the country (28 % of the total acreage), and just 8 % in the South, including the islands (less than 5 % of the total acreage). Even though these statistics provide a plausible summary of hop cultivation in Italy, fragmented information and missing data lead to suppose that, presently, hop gardens cover an area larger than 52 ha.

Table 1
Hop production area (ha) and number of hop growers in Brazil by state.

State	Hop production area (ha)	Number of hop growers
Santa Catarina	34	19
Sao Paulo	25	27
Minas Gerais	21	7
Rio de Janeiro	11	8
Parana	8	16
Rio Grande do Sul	7	11
Others	6	26
Total	112	114

Source: Aprolúpulo (2023).

Regarding hop varieties, Cascade is, by far, the most studied cultivar followed by other American hops such as Chinook, Columbus, Comet, and Nugget. European cultivars were rarely tested. Cone yield markedly varies principally based on plant age, pedoclimatic conditions, agronomic management and cultivar. However, the few agronomic studies conducted in Italy until now showed a promising yield potential, ranging roughly from 1 to 2.5 t ha^{-1} (Ruggeri et al., 2023a).

2.2. Brazil

The Brazilian beer production is approximately 16 billion L year^{-1} and represents around 2.0 % of the national gross domestic product, with annual revenue of 28.7 billion euros (€) and is one of the most important sectors in the Brazilian economy. However, Brazil imports over 98 % of the hops needed for the brewery industry and, in 2021, 4700 tons were imported, mainly from the United States and Germany, for a total of 521 million € (Comex-Portal do comércio exterior do Brasil, 2022; Ibge - Instituto Brasileiro de Geografia e Estatística, 2020; Mapa - Ministério da Agricultura e Pecuária, 2022).

Currently, growing hops in the country is considered a novelty. Even though some attempts to grow this species took place in the past, mainly by European immigrants, just in the mid-2000s hop cultivation escalated to a higher level when the number of new craft breweries increased across the country and started to demand diverse raw material to produce different types of beers. Concomitantly, hop cultivars from Europe and US were introduced by new established hop nurseries, as well new growing technologies were developed by some research institutions (Arruda et al., 2021; Guimarães et al., 2021; Simieli et al., 2021). Among these technologies, supplemental lighting to control the growth of plants stands out. The use of LED lamps with a specific spectrum is needed mainly because, in Brazil, the maximum daylight period reaches around 14 hours, which is lower than the required by hops to promote growth during the early growing season (17 hours). This was one of the main causes of the failure of hop cultivation in the country in the past (Jastrombek et al., 2022).

Given the growing interest in hop cultivation in Brazil, in 2018, the Brazilian Association of Hop Producers – Aprolúpulo – was founded with the objective of gathering information and promoting hop cultivation in the country (Muller and Marcusso, 2018). According to a survey carried

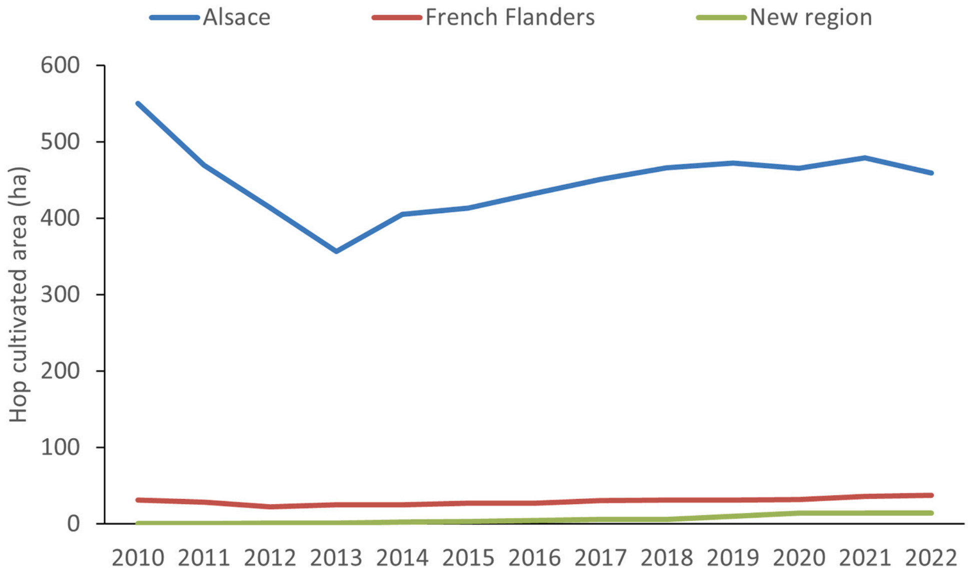

Fig. 3. Evolution of hop cultivated area in France from 2010 to 2022 (Agreste, 2023).

out in 2023 by Aprolúpulo (Aprolúpulo, 2023), currently, the cultivation of Brazilian hops is spread over 112 ha in regions of different latitudes and climates (Table 1), especially in the southeast and the southern regions of the country, which represents a 133 % increase of the growing area as compared with 2022. In addition, these regions have the highest concentration of hop growers and breweries in the country, accounting for 86 % registered industries.

On average, each grower cultivates around 1 ha of hops, and 38 % of them declared the wish to increase the hop area in 2024. In 2023, 88 tons of hops were produced in Brazil, which represents an increase of

Fig. 4. Hop cultivated area (ha) in French regions in 2022 (Interhoublon, 2023).

203 % compared with 2022. In terms of yield, 787 kg ha^{-1} was the average recorded in 2023, but the average production was 379 g per plant, and this value tends to increase because of the young age of the plants in most of the hopyards. The main five cultivars grown in the country are Comet (31.6 %), Cascade (24.1 %), Saaz (11.1 %), Chinook (6.4 %) and Zeus (5.2 %), however, several other cultivars were recently introduced and their performance area under evaluation. Usually, growers market their hop production mainly as dried pellets packaged in modified atmosphere and, over 83 % of the growers, declared to provide information about the chemical properties of the processed hops in the label. Depending on the quality of the produce, the price of 1 kg of processed hops can reach around 72 €, but the average price recorded is currently around 40 €.

Due to the climatic conditions in Brazil, with short and mild winters, the production of two crops a year has been possible in some regions (Leles et al., 2023), while in regions following traditional cultivation practices, only one cycle is obtained per year (Guimarães et al., 2021). These hop cultivation initiatives have generated great enthusiasm for the production of this important raw material for the brewing industry. In addition, Brazilian hops have shown distinct characteristics in terms of bitterness and aroma when compared to imported products, which have led to the production of beers with typicity (Almeida et al., 2021).

Brazil has great potential to expand the hop cultivation areas in the upcoming years. The interest in expanding the production chain has led to the union between public research institutions and private companies, such as AMBEV (Americas' Beverage Company), with the aim of generating, expanding and disseminating knowledge about the production of high-quality and sustainable raw materials in the country.

2.3. France

France is the 5th beer producer in Europe, with 2 billion L of beer produced in 2022, representing a total of 6 % of European beer production (Eurostat, 2023). In addition, France imported 0.9 billion L and exported only 0.4 billion L. As a consequence, the national needs in hop acreage to supply all the breweries is estimated between 2000 and 2500 ha, representing around 3000 tons (t) of production. In 2023, national hop production reached 836 t (IHGC, 2023). The imports mainly originated from neighbouring countries, with Germany and Belgium representing respectively 69 % and 18 % of the total external hops.

In France, two hop-growing regions historically led the hop production since 19th century: Alsace and French Flanders, located in the Northeastern part of France. European and French hop varieties are grown. Hop production in France is strongly correlated to beer market and evolution of hop surfaces throughout the 20th century and it fluctuated in response to crisis and expansion of the national and European beer industry (Gillard, 2023).

The rise of craft breweries in the last decade is very much transforming hop production. Indeed, since 2013 their number has exponentially increased from 529 in 2013 to 2513 in 2022 (Gillard, 2023). The demand in national hop and organic hop increased all over French territory in the last decade and it was higher than the supply in 2016 (Gillard, 2023; Agence Bio, 2023; Dauger, 2022). As a response, hop cultivated area and hopyard locations significantly evolved in France (Fig. 3).

An increase in hop acreage was firstly observed in Alsace in 2014 while, in the other historical hop production area (French Flanders), hop acreage remained stable. In a second stage, since 2018, hopyards were planted in the other French regions and in 2022, as a result, hops represented 672 ha in France (Fig. 4).

The increase in hop acreage was accompanied by several mutations in hop farming such as the development of an organic production and a greater diversification in growing practices, types of farmer, and hop varieties (Agence Bio, 2023; Dauger, 2022). The development of organic hop production in France is associated with the increasing demand of craft breweries. The first grower started in Alsace at Agricultural School of Obernai in 2012 with 18 ha (Dauger, 2022). Then, organic hop farming expanded in Alsace and in the new producing regions. In 2021, the organic hop acreage reaches 204 ha, including 71 ha in conversion and 133 ha certified as organic (Agence Bio, 2023). This recent expansion of hop production outside of Alsace and the French Flanders is led by neo-growers and has profoundly mutated hop cultivation in France. Indeed, hop acreage per grower in the new hop growing regions is comprised between 1 ha and 4 ha and neo-growers are mainly producing organic hop (Agence Bio, 2023).

Regarding hop varieties, geographical expansion of hops in France is an opportunity to introduce new varieties. In Alsace regions, the main varieties are Strisselspalt, Aramis, Fuggle, Savinjski Golding, Triskel, Hallertau Tradition and only 14 ha of bitter varieties. Despite the lack of official data outside of Alsace, the Agence Bio, 2023 indicates a list of varieties cultivated by the interviewed neo-growers: Cascade, Chinook, Nugget, Magnum, Fuggle, Brewer's Gold, Golding, Centennial, Barbe rouge, Tradition. This list illustrates the strong presence of American cultivars in the new hop growing regions that are better adapted to southern pedoclimatic conditions. It also reveals that, with the exception of Alsatian commercial varieties, public cultivars are selected by neo-growers due to their availability (Agence Bio, 2023). Nevertheless, this list of cultivars available in French hop market does not entirely fulfill craft-brewers needs mainly oriented towards American commercial cultivars (Furet et al., 2018; Gillard, 2023).

2.4. U.S.A.

The total volume of beer sold in the US was 20.3 billion L in 2023, of which 2.7, 4.7, and 12.9 billion L were from craft beer, imported beer, and other domestic beer, respectively (Brewers Association, 2023a). The retail sales of craft beer accounted for 24.7 % (25.9 billion €) of the 104.8 billion € beer market. In 2022, United States exported 267 million € worth of hops and imported 60.1 million € worth of hops (Observatory of Economic Complexity, 2024).

In the United States, the majority of hops are produced in three northwestern states, Washington, Idaho, and Oregon, collectively known as the Pacific Northwest (PNW). In 2023, the Pacific Northwest produced 47,193 t of hops on 21,982 ha, accounting for 98 % of the national hop production (Hop Growers of America, 2024). Because of recent growing demands for locally grown hops among craft breweries, many other States have attempted to produce hops locally. Some states, like Michigan, Montana, Indiana, and Ohio, successfully established regional hop cultivation. Hop production has also returned to New York, which used to be the leading hop producing state until uncontrolled fungal diseases diminished the local hop production in the early 20th century (Cornell Cooperative Extension, 2024). In 2023, hops were harvested on 563 ha outside the Pacific Northwest, of which 154, 121, 80, 32, and 26 ha were located in Michigan, New York, Montana, Indiana, and Ohio, respectively (Hop Growers of America, 2023).

2.4.1. Virginia

As one of the earliest territories to be settled by English colonists, Virginia served as a test site for all manner of crops and practices imported from continental Europe. There are records, and anecdotal evidence to suggest that beer production was one of the earliest industries to take hold in the colonies, and that hop production soon followed in order to support the nascent brewing industry. Hops were used to brew what was called 'small beer', made by mixing, boiling, and fermenting molasses, wheat bran, hops and water. The low-alcohol beer, pasteurized by the boiling step was safer to drink than water, and home brewing was common. Almost all families made their own beer to be drunk even by children, and commercial brewing was not yet common. Records indicate that there were only two breweries in Williamsburg in 1780 when the capital relocated to Richmond (McDonald, 2014).

Thomas Jefferson, famous Virginia resident and President of the US from 1801 to 1809 planted hops in his Monticello Estate in Albemarle County. Judging by his records, the estate also purchased various amounts of hops from other growers between 1771 and 1820, most likely, for brewing batches of small beer. In his notes on the State of Virginia, Jefferson identifies hops as one of native plants growing in Virginia and confirms cultivation of the crop in his own estate in his garden calendar, and lists of 'objects for the garden' in 1794, 1812, and 1813. These and other Jeffersonian records are maintained by the Massachusetts Historical Society (https://www.masshist.org/thomasjeffersonpapers/).

A brief history on the introduction of hop culture into the US, and the eventual localization of commercial production in the Pacific Northwest is provided by Brooks et al. (1961). According to existing records, hops were introduced into North America by the Massachusetts Company in 1629, and the crop was grown for domestic use in New Netherlands as early as 1646. New Netherlands was a 17th-century colonial outpost of the Netherlands located on the east coast of the US. The territory encompassed modern-day New York, New Jersey, Delaware, Connecticut, and small portions of Pennsylvania and Rhode Island. By 1648 hop production had spread to Virginia. However, hops did not become an important cash crop in the US until the establishment of the first commercial hopyard in New York around 1808. By 1849 New York, produced more than a million pounds (approx. 450 metric tons) of hops annually and total annual production along the east coast totaled about 1.5 million pounds (approx. 680 metric tons). Following the Civil War, hop production spread rapidly through Pennsylvania onward into Wisconsin where 5 million pounds (approx. 2300 metric tons) were produced in 1869. During the same period, production in New York increased to more than 21 million pounds (approx. 9500 metric tons), but the hop industry in New York was decimated by downy mildew (*Pseudoperonospora humuli*) in the 1920's, and the state stopped being an important hop producer after the first World War. Hop production shifted to the Pacific Northwest (PNW) between 1849 and 1869 and although New York was still a leading producer at the turn of the century, it was outpaced by Oregon and California by 1909. Washington, California, and Oregon remained the major hop-producing States up to 1950 when production started to increase in Idaho, and to decline in California (Brooks et al., 1961). Data from the 2022 USDA Census of Agriculture shows that Washington State currently leads US hop production with 17,433 harvested hectares, followed by Idaho (3960 ha), and Oregon (3174 ha). California recorded only 25.5 harvested ha during the same census (USDA-NASS, 2024).

In spite of these developments, low-scale hop production persisted in Virginia, led by a few dedicated hobbyists interested in homebrewing. Renewed interest in hop production in Virginia was ignited by the rapid growth of craft brewing in the 21st century. Although modern US craft brewing began in the 1960s, the rise of microbreweries starting in the 1990s was followed by explosive growth from around 2010 that saw the number of craft breweries increase from 103 in 1972 to 9247 in 2021. Fig. 2 shows the change in the number of craft breweries in Virginia over the same period (2011 - 2022).

The emergence of craft brewing as an important economic driver quickly translated into demand for local ingredients among brewers interested in promoting authentic Virginia beers, and landowners started to express interest in barley and hop production to meet the demand. On the hops side, the Virginia Department of Agriculture and Consumer Services, in 2015, awarded hop research initiation funds to the two land-grant institutions (Virginia State University and Virginia Tech) in the Commonwealth with the charge to identify hop varieties and agronomic practices suited to the region, and to support landowners interested in growing the crop.

2.4.2. Florida

Florida is a southeastern state in the United States, where climates are classified as subtropical or tropical. In 2015, commercial hop production was nonexistent in Florida. In 2023, there were at least 4 growers producing hops on about 2 ha (personal communication with local growers). Although hops are still a minor emerging crop in Florida, interest in locally grown hops has been increasing among Florida craft breweries. In 2023, Florida had 404 craft breweries, which produced 158 million liters of craft beer and generated an economic impact of 3.8 billion € (Brewers Association, 2023b). According to the survey conducted by Hambaryan et al. (2023), 98 % (41 out of 42) of participating Florida craft breweries indicated the Pacific Northwest as a major source of domestic hops. The huge potential market for locally grown hops may support the further growth of hop production in Florida. Despite the very limited production, the demand for locally grown hops is huge in Florida.

Table 2
Agronomic strategies mostly advocated for organic hop production.

Agronomic strategy	References
Selection of cultivars based on their adaptability to pedoclimatic conditions and methods of cultivation (e.g., low- vs. high-trellis system, organic vs. conventional farming)	(Carrubba et al., 2022; Lutz et al., 2023; Rossini et al., 2016)
Determination of the adequate soil chemical and physical properties and implementation of appropriate soil tillage, irrigation and drainage system	(Cancela et al., 2022; Fandiño et al., 2015; Ruggeri et al., 2023b)
Development of protocols to manage weeds without chemicals (e.g., using mulching, cultivation, physical methods, etc.)	(Lipecki and Berbeć, 1997; Moretti, 2023; Turner et al., 2011)
Adoption of suitable cover crops to i) control weeds, ii) supplement nitrogen needs, iii) prevent erosion, iv) enhance soil physical properties and v) reduce mite populations by creating a favorable habitat for beneficial predators	(Obermeier and Goldbrunner, 2023; Turner et al., 2011)
Use of organic fertilizers (e.g., livestock-based manure, composts, etc.), including waste hop biomass, to enhance and/or retain soil fertility through the growing season	(Amoriello et al., 2020; Čeh et al., 2023; Turner et al., 2011)
Identification and timely application of foliar fertilizers, biostimulants, predatory mites and biocontrol agents to provide balanced nutrition to the plants and protect them from diseases and pests	(Afonso et al., 2021; Procházka et al., 2018; Rodolfi et al., 2023, 2021; Testa et al., 2023; Vostřel et al., 2023; Weihrauch et al., 2023)
Selection of the best planting material and optimization of plant density per unit area	(Iacuzzi et al., 2023; Kořen, 2007; Marceddu et al., 2020)

3. Agronomic research to support hop farmers

3.1. Italy

One of the major limitations to the introduction and development of a new crop species is the access to technologies such as seed or seedlings, fertilizers, water, marketing, storage, processing, and plant protection products. This latter aspect has heavily influenced the way hops is currently cultivated in Italy. Given that no synthetic pesticides are registered yet for the use on hops, the only difference between organic and conventional hops is the application of chemical fertilizers. As a consequence, the area under organic production system dramatically increased in the last years, moving from 3.3 ha in 2016 to 45.4 ha in 2020 (https://innovaluppolo.crea.gov.it). Even though the appreciation for organic beer is controversial in Italy (Bimbo et al., 2023; Lerro et al., 2020), organic certification could be used to generate differentiation strategies in the global beer market for the future (Capitello and Todirica, 2021).

Sustainable management of crops implies a holistic view and an

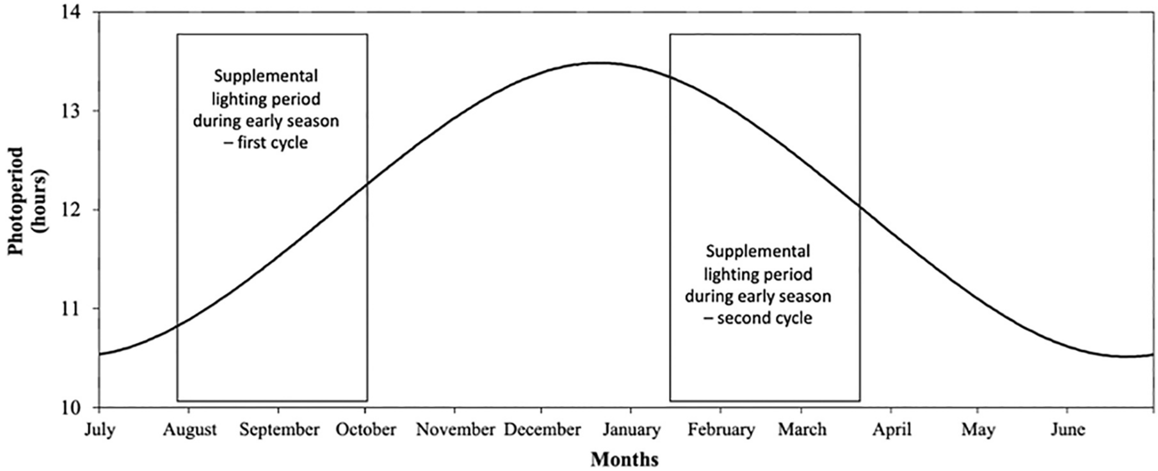

Fig. 5. Photoperiod (hours) along the year in Brazil (latitude 24°, Southern hemisphere), and supplemental lighting period during early season in both first and second cycle seasons.

integrated approach to use efficiently the natural resources, while preventing and controlling plant diseases, pests and weeds. Particularly, agronomic knowledge should markedly increase as technical tools availability decrease. Therefore, the role that agronomy plays in organic farming is of paramount importance as compared to other production systems. Agronomic strategies and practices, which mostly contribute to a successful hop production under organic farming, are reported in Table 2. Another pivotal aspect for organic systems is crop genetic improvement. Agronomic qualities that are crucial for organic hop growers and can be driven by breeding activity include disease and pest resistance as well as nutrient-use efficiency (Turner et al., 2011).

A preliminary assessment of bibliography, conducted using Scopus database, revealed that Italian scholars published 14 field studies addressing agronomic issues of hop farming from 2016 to the first months of 2024. The vast majority of these studies (10 out of 14) aimed to evaluate the adaptation of hop commercial cultivars to different environments along Italy. More in detail, three studies were conducted in Lazio (Rossini et al., 2020, 2016; Ruggeri et al., 2018), three studies in Sicily (Carrubba et al., 2022; Marceddu et al., 2024, 2020), one in Sardinia (Forteschi et al., 2019), Calabria (Gresta et al., 2022), Marche (Mozzon et al., 2020) and Emilia-Romagna (Mongelli et al., 2016). The interest in exploring the hop plant response in central and southern regions more than in northern ones is likely based on the positive experience that the Italian hop pioneers already had in the northern part of the country. All these studies highlighted the good or even excellent performances of hops regarding both yield potential and quality features.

As for the other four studies, two refer to the same experiment and aimed to investigate the effect of different organic foliar fertilization plans on physiological and quality traits of hops (Rodolfi et al., 2023, 2021). One is related to the evaluation of spent grain biochar impact on hop growth (Amoriello et al., 2020), and the last one represents the first attempt to assess the yield potential of an organic commercial hopyard during its establishment period in central Italy, with a focus on the relationship between yield and soil texture (Ruggeri et al., 2023b).

However, from an agronomic point of view, almost all of these studies display one or more important limitations:

- Short duration of field experiments: 5 studies were carried out in a single season and location (Amoriello et al., 2020; Gresta et al., 2022; Mozzon et al., 2020; Rodolfi et al., 2023, 2021);
- Restricted sample size: The majority of studies reported data obtained by sampling less than 10 plants per replicate;
- No accurate description of the agronomic practices applied during the study;
- Just few data on hop phenology, growth and yield: many studies reported only the phytochemical composition of cones.

Another study, recently published, aimed to develop a new micropropagation protocol for hops (Iacuzzi et al., 2023). Although it was not a field trial, it is closely related to the production and selection of excellent planting materials.

The difficulty to gain scientifically sound agronomic data in new growing areas lies in: i) the particular trellis system required for proper hop growing; ii) the high cost of these structures; iii) the labour-intensive management of hop gardens (Marceddu et al., 2023). Consequently, well-designed, and properly managed experimental hopyards are extremely rare in Italy. Reliable data for research could be obtained from commercial hopyards, but several complications often arise because of the distance of fields from the Universities or the Research Centers and the inability to strictly supervise the activity of hop growers during the experiment. Additionally, many Italian hop growers are not professional farmers but more often brewers, pub owners, beer sellers and others, who need assistance from a careful agricultural extension service.

Finally, Italian researchers published two reviews on agronomic aspects of hops. The first, deals with the difficulties and opportunities of hop cultivation in the Mediterranean environment, under both conventional and organic farming (Rossini et al., 2021), while the other provides an in-depth investigation of the available literature on the response of hop plants to abiotic stresses such as salinity, heat, and drought (Marceddu et al., 2022). In the context of climate change, this topic will gain more and more interest especially under Mediterranean climatic conditions (Kind and Kaiser, 2020; Kolenc et al., 2016; Nesvadba et al., 2023).

3.2. Brazil

Interest in hop cultivation in Brazil has increased with the influence of adapted technologies, the manipulation of the species by crossbreeding for genetic improvement and the possibility of adaptation to local conditions (Muller and Marcusso, 2018). This escalation of interest, both in the cultivation and commercial exploitation of hops, has attracted important investments for its establishment on the national level. The major challenge for the development of hop production in Brazil is the adaptation of cultivars to the diverse geographic and climatic conditions. High yield capacity and local "terroir" are two desirable features to meet the growing demand for raw material by the brewing industry.

Some significant achievements were reached so far, and currently,

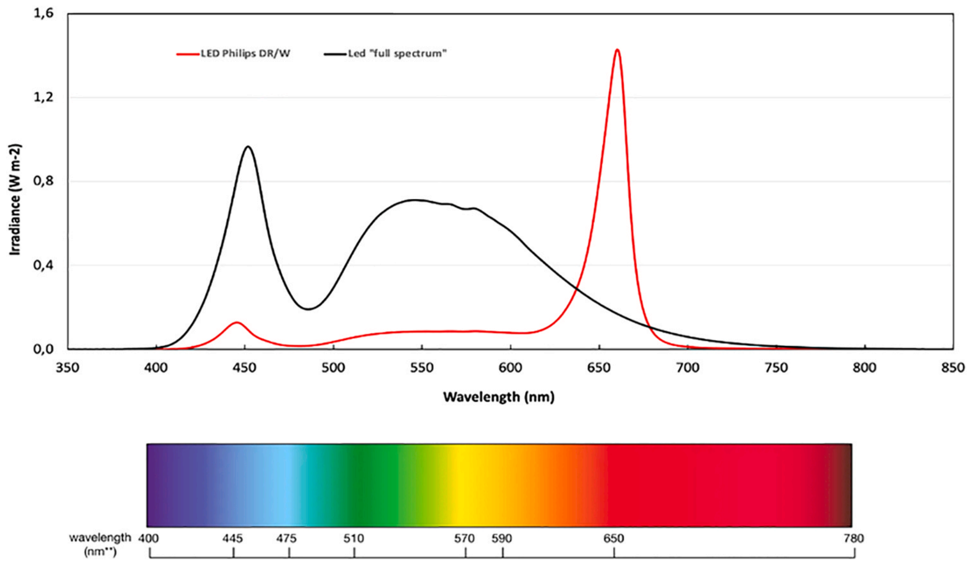

Fig. 6. Irradiance (W m^{-2}) of the Philips GreenPower LED DR/W and a "full- or broad-spectrum light" LED according to the wavelengths emitted (nm).

over 50 hop cultivars are registered in the Ministry of Agriculture, Livestock, and Food Supply (Mapa, 2022). Most of these cultivars are available for sale by suitable hop nurseries, such as Ninkasi, Hops Brasil and Van de Bergen, which have provided a supply of plants of different cultivars and of high genetic quality. It is one of the main components of a high successful production system, because not suitable nurseries, mostly not officially registered, still offer online hop young plants with no certification of origin.

The duration of the cycle of hop cultivars, including the duration of each phenological phase, has been pursued by various researchers in Brazil, aiming to identify the more suitable genotypes for two crops per year system, as well to determine the most appropriate periods for harvesting according to the climate conditions of a region. The findings of Leles et al. (2023) were quite enlightening about the cycle duration of various hop cultivars grown under two crops per year system in a subtropical area with supplemental lighting. The authors reported that Mapuche, a hop cultivar from Argentina, is considered an early genotype, while the cultivars Hallertau Mittelfrüher and Northern Brewer are considered late genotypes. These findings may help to optimize some laborious agricultural operations, such as harvesting and processing, allowing for better planning of the production system.

The air temperature is an important climatic element for the production of hops, and it greatly influences the timing of the initiation of the growth of plants after the winter, which determines the harvest season of cones (Pavlovic et al., 2012). In high latitude regions of Brazil where the winter season (July to September) is more severe and lasts longer, cut back hops tend to regrow from mid-September (early spring), and cones are harvested from February to early March (late summer) of the following year, with the exact timing depending on the cultivar. On the other hand, in regions with mild winters, which has a low risk of frost, cut back hops regrow from late July (mid-winter), and cones are harvested in mid-December (early summer). This is interesting from the point of view of maximizing crop production in these regions, since after harvesting, it is technically possible to promote a second production cycle by applying a second cut back (Fig. 5). Indeed, air temperature remains high until late April, thus allowing a good vegetative development of the plants (Jastrombek et al., 2022). Researchers are looking for ways to maintain the yield of hops grown under two crops a year system, mainly because the climate conditions of each one is quite different, and may affect the quality of processed hops.

The use of the supplemental lighting can be considered, along the introduction of adapted cultivars, a turning point for successful hop production in Brazil, where natural day length induces premature flowering and does not promote adequate bine growth. This technique has been used in different areas of Brazil, and some specific characteristics of the LED lamps, such as spectrum, light intensity, spacing, density and costs per hectare are being assessed (Leles et al., 2023).

The use of supplemental lighting to inhibit the flowering of some short-day ornamental plants grown under protected cultivation, such as chrysanthemum, has been used for several decades, mainly by using incandescent lamps (Moura et al., 2014). However, due to the high cost of this type of lamps, including energy consumption, they were never considered to be used in open fields for hop cultivation. More recently, when the light-emitting diode (LED) technology was developed for plant growth, the production of short-day species was improved and optimized by using LEDs with a specific spectrum (Trivelline et al., 2023), resulting in energy savings of up to 90 % compared with incandescent lamps. Therefore, the idea to grow hops in Brazil re-emerged within the research community by using supplemental lighting with LEDs. After the pioneer findings of Agehara (2020) in Florida (US), who first described the use of supplemental lighting for hop growing in open fields by using a LED designed for short-day species, the search for various types of LEDs, such as bulbs and reflectors with different light intensities and spectra, started in the country. In addition, it must be considered that the national hop demand was also influenced by the search from the brewery industry for freshly hops, requiring shorter storage time, as the hops lose quality in the pelleting process due to oxidation and degradation of their chemical compounds over time (Durello et al., 2019).

However, it has been observed that some hop growers do not pay attention on some growing technologies such as the use of LEDs with a specific spectrum for flowering control. On the contrary, inappropriate lamps, not designed for plant grow control, are being used with no scientific criteria. One of these lamps is the LED reflector used for outdoor lighting, usually called as "full- or broad-spectrum light", with low red wavelength (650 nm, Fig. 6). A full-spectrum grow light is a simple marketing term that implies that this grow light closely resembles light from the sun, but the plant's response to light is quite different. Because of the use of inappropriate lamps, the hop yield is low, and the production cost is increased.

According to our experience, the professional LED grow light has four characteristics that define the optimal growth of hops, as follows: i) the light level or the photosynthetic photon flux density (PPFD), which is the amount of light that actually arrives at the crop canopy in the photosynthetic active radiation (PAR) zone, expressed in μmol m^{-2} s^{-1};

Fig. 7. Hop plants grown in Brazil with supplemental lighting (Philips GreenPower LED DR/W 10 W) during the early season to promote bine growth and avoid premature flowering.

Fig. 8. Hop plants grown under two crops a year system in mild winter Brazilian regions. A: Hop plants reach the top of the trellis by using supplemental lighting during the early season to promote bine growth; B: After reaching the top, supplemental lighting is turned off, and the emergence of flowers begins.

ii) the specific light spectrum or wavelength expressed in nm, with high red content for high efficiency; iii) the light uniformity, i.e., uniform light levels across the crop for consistent growth, with an overlap area that permits an efficient distribution of light; and iv) the time, i.e., the moment of switching on/off the LEDs according to the photoperiod of a given location.

Some LEDs were designed to attend these characteristics and to control the flowering of short-day plants, such as the Philips GreenPower LED DR/W 10 W flowering lamp (https://www.assets.signify.com/ is/ content/Signify/Assets/philips-lighting/global/20200929-phil-ps-flowering-lamp2.1–442295201951-a-d03.pdf), which offers a combination of deep red and white spectra (Agehara, 2020). Besides, this LED spectra contain relatively little green light, which facilitates the field inspection at night, if necessary (Fig. 7). Because this bulb is made of a white frosted plastic (glass-free), it is light in weight (170 g), with a nominal average lifespan (L90) of 25,000 hours, thus resulting in a low consumption of energy and a long period of use in open fields.

Depending on the latitude of a given location, some adjustments are required when supplemental lighting is used to manipulate the growth of hops. Basically, the lower the latitude of a given location is, the greater the number of hours of artificial lighting required during the early season. Besides, the daily photoperiod along the year should be known to correctly calculate the daily period that the LEDS will be turned on and off to reach the 17 hours during the early season. This is especially important in areas where hops are grown under two or three crops per year, because the photoperiod changes along the year as previously shown in Fig. 5. Hop plants normally begin developing flower buds within a few days after the termination of photoperiod extension, and as a result, an impressive increase in yield has been observed for several hop cultivars grown under this technology (Fig. 8).

However, if the sizing of LEDs is not sufficient, the light level may not arrive for all plants, and an erratic development is observed in the hopyard, especially in those plants located in the borders, as well in those in which the overlap of light distribution is not sufficient due a flaw of the layout design (Jastrombek et al., 2022).

3.3. France

The recent evolution of hop production in France implies developing research to elaborate new agronomic hop references at national scale. The main concerns to improve cultural practices, yield and quality in the new hop producing regions are: plant requirements, agronomic strategies, yield and quality potential determination. Nevertheless, as hop is an orphan crop in France, no research center is dedicated to hop. As a result, agronomic studies are led by agricultural organisms and private companies providing agronomic consulting services. The Agricultural School of Obernai and the Alsatian hop cooperative historically possess the agronomic knowledge and innovation leadership working in collaboration with German and English researchers. Their research subjects are focused on improving farming practices, pest and disease management and hop breeding (Laugel-Niess and Dauger, 2022).

In the new hop growing regions, local hop growers work in association with agricultural institutes (agricultural chambers, organisms dedicated to organic farming development) about hopyards design, studies to adapt cultural practices to local pedoclimatic conditions, organic and agroecological practices, knowledge transfer (Agence Bio, 2023). Technical guides and training courses are available as outputs of these collaborative works (Frichot et al., 2023; Furet et al., 2018).

As hop cones contain several interesting molecules with potential markets in the health, cosmetic and food industry, research about new possible outlets for hop is sporadically conducted (Bocquet et al., 2018). Also, as a potential tool for cultivation and breeding, the genetic diversity of wild hops was investigated (Paguet et al., 2023). Nevertheless, as a perennial crop, hop is facing long term challenges such as adaptation to climate change (Loussert, 2023). To this end, research about the adaptation of cultivars to different agrometeorological conditions, irrigation monitoring and mitigation of climate change through the adaptation of cultural practices should be developed as well as maintaining breeding development.

In this regard, a breeding program was initiated in Alsace in early 2000's. Thanks to this program, the varieties 'Aramis', 'Barbe Rouge', 'Triskel' and 'Elixir' were commercialized. Currently, in order to better fulfill the needs of all French hop growers, a national breeding program is envisioned (Interhoublon, 2023).

3.4. U.S.A.

3.4.1. Virginia

There are reports of heritage hops in Virginia, some claimed to trace their roots back to Monticello, but there are no local varieties in commercial production. Thus, trials were conducted to identify cultivars and agronomic practices for commercial hop production in Virginia. We started by selecting from existing varieties, those with the greatest chance of success in the mid-Atlantic region. Personal communication from hobby growers identified 'Cascade', a mainstay for Virginia homebrewers, as the cultivar proven to do well under local conditions, and it was subsequently included as a control in field trials. Studies to test the performance of select, public-domain varieties in Virginia, were conducted by Virginia State University (VSU) and Virginia Tech (VT).

Both trials provided useful information about agronomic performance of some commercial cultivars and their interaction with pests and pathogens under different climatic conditions of Virginia. This enabled new growers to make a conscious cultivar choice, thus reducing the risk of crop failure. For example, Cascade, Nugget, Crystal, and Comet showed the highest potential for this region, while Centennial, Mt. Hood, Southern Brewer, Sorachi Ace and Ultra the lowest one. Another precious outcome of these studies was the diagnosis of nutrient deficiencies in hop plants. This information can be used to better understand hop nutrient uptake and the complexity of nutrient deficiencies, thus helping hop growers to detect nutrient deficiencies and know when to conduct tissue tests for fertilization controls (Judd, 2018; Rutto et al., 2021).

Analysis of petiole samples showed mineral content comparable to sufficiency reference data published by Sirrine (2016), suggesting that nutrition was not a significant factor in cultivar performance at both sites. However, cone quality varied widely among cultivars, and only a few met published thresholds for acid and essential oil content (Yakima Chief Hopunion, 2024).

Alongside the two agronomic trials, other hop-related research and outreach activities have been conducted to support and inform the industry. Guidelines on requirements and cost estimates for building a half-acre hop yard in Virginia were published by Rutto (2015), and Siegle and Scoggins (2019), (2017) conducted grower surveys that kept track of growers adopting hops as a crop. Their findings show that adoption as measured by number of new growers, and crowns planted rose from 2010 and peaked in 2014 (Siegle and Scoggins, 2018). Other extension publications on hops in Virginia include a guide on irrigation management by (Jackson et al., 2019), and an article by Liu et al. (2023) that discusses changes in cone quality of Virginia grown hops during ripening. Detailed characterization of aroma compounds in Cascade and Chinook hops harvested from multiple Virginia locations showed significant variation in quality, suggesting that environmental factors and agronomic practices are key determinants of hop chemistry (Su and Yin, 2021).

Results from the two agronomic trials exposed serious challenges to commercial hop production in Virginia. Market trends also showed clear preference by most craft breweries for proprietary cultivars with complex character, all of them developed by private sector breeders in the PNW (Comi, 2024). The hop industry in the PNW is flexible and highly efficient as demonstrated, for example, by reports from east coast craft brewers that growers in the PNW can deliver fresh hops for wet-hopped beers overnight, thereby undercutting a key selling point for locally-grown hops.

In response to these observations, research at the two universities in Virginia, and at other institutions in the region have been scaled back. At VSU, a discussion is ongoing on whether to continue low-trellis hops research on-farm. In neighboring North Carolina, North Carolina State University has opted to invest in a breeding program with the long-term objective of developing cultivars suited to the eastern US. According to a report during the 2020 meeting of the American Society of Horticultural Science (ASHS), the program is now conducting on-farm trials and brewing evaluations of four promising selections.

Hop growers in Virginia have similarly responded to the various challenges in different ways. Some have discontinued hop production, while a few with steady markets based on strong relations with home brewers and local craft breweries remain in business. Some farms like

Fig. 9. 'Cascade' hops grown with photoperiod manipulation under subtropical climatic conditions in Florida. A: Plants at the bine elongation stage; B: Plants at the harvest stage. Photoperiod extension with LED lighting suppresses flowering and promotes vegetative bine growth. Flowering is induced by discontinuing photoperiod extension.

Mountain View Hops (https://mountainviewhops.com/) have developed non-beer hop products and continue to explore other niche markets.

3.4.2. Florida

The world's two largest hop production regions, Hallertau in Germany and Yakima in the United States, are located at 48.6°N and 46.6°N, respectively, where the maximum day length exceeds 16 hours. Compared to these regions, Florida is located at much lower latitudes, ranging from 24°N to 30°N, with the maximum day length of only about 14 hours. Flowering of hops is induced when day length becomes shorter than the critical day length, generally 15 hours (Neve, 1991). To ensure high productivity, hop plants must achieve adequate vegetative growth before flowering is induced. Therefore, insufficient day length is among the major environmental constraints for hop production in Florida and other subtropical and tropical regions. Acosta-Rangel et al. (2021) conducted a field experiment to examine phenology, growth, and yield potential of 15 hop cultivars under Florida's natural day length conditions. All tested cultivars induced flowering at a premature growth stage, resulting in poor vegetative growth and very low yields, ranging from 0 to 197 kg ha^{-1} in the establishment year (Acosta-Rangel et al., 2021).

To overcome this climatic constraint, Agehara and his research team at University of Florida examined the effectiveness of photoperiod manipulation in controlling the timing of flowering (Acosta-Rangel et al., 2024; Agehara, 2020). They installed light-emitting diode (LED) lamps (GreenPower LED flowering lamp DR/W; Koninklijke Philips N. V., Amsterdam, Netherlands) on trellis cables that were 5.7 m high from the ground (Fig. 9). At the ground level, the fluence rate of the LED lamps was only about 1 µmol m^{-2} s^{-1}, produced primarily by red light (Acosta-Rangel et al., 2024). Despite the very low fluence rate, they found that extending the photoperiod to >16.5 hours using the LED lamps is an effective strategy to promote vegetative growth by inhibiting premature flowering. Uniform flowering was induced upon the discontinuation of photoperiod extension. Furthermore, they demonstrated that the flowering control by photoperiod manipulation enables double production cycles of hops per year in a subtropical climate. The annual yields of 'Cascade' hops in the establishment and second year were 369 and 707 kg ha^{-1}, respectively. They also reported that the spring-season yield was 1.6 times higher than the fall-season yield.

Other agronomic practices have also been studied. Acosta-Rangel et al. (2021) evaluated the effects of hill spacing (76, 91, and 107 cm) and nitrogen (N) rate (109 and 130 kg ha^{-1}) on the performance of 'Cascade' hops under Florida's natural day length conditions. The yield in the establishment year increased with reducing hill spacing and increasing N rate by 41 % and 38 %, respectively. In their study, however, plant growth and yields (78–112 kg ha^{-1}) were limited because of premature flowering. Therefore, these agronomic practices need to be reevaluated in combination with photoperiod manipulation.

Since 2020, Agehara and his research team has been evaluating the effects of two trellis designs (straight trellis and V-trellis) and three trellis heights (3.7, 4.6, and 5.5 m) on growth, morphology, yield, and cone quality of 'Cascade' hops grown with photoperiod manipulation. The straight trellis had two twines per hill installed on a top middle cable, whereas the V-trellis had four twines per hill installed on two top parallel cables. In general, yields were higher for the V-trellis than for the straight trellis and increased with increasing trellis height.

Gallardo et al. (2022) studied the importance of postharvest pruning as a hopyard management practice. In Florida, the optimum time to prune remaining bines after harvesting (about 1-m bottom section) differs between the spring and fall seasons because of different postharvest growing conditions. After the spring harvest, they recommend pruning all remaining bines immediately at the ground level to encourage the emergence of new bines from rhizomes. After the fall harvest, leaving unharvested bines to senesce in the field can promote the translocation of nutrients in stems and leaves to rhizomes and roots. When the bines are completely senesced, they recommend pruning them back at the ground level. Proper postharvest pruning can not only enhance the following season's crop performance but also improve pest management and facilitate other cultural practices in the hopyard.

4. Conclusions and the way forward

It emerged from this review that the craft beer revolution was the driving force moving different countries to explore the possibility of growing hops outside its traditional borders. Indeed, the development of new beer recipes with local attributes created new business opportunities also in territories characterized by environmental conditions very far from those in which most of the global commercial production is obtained.

Growing well-adapted and high-yield cultivars with the appropriate technology and management practices is the target shared with all the new hop growing areas. A deep and constant research activity in agronomy is the only way to address this challenge and, consequently, to lay the foundations for the creation of a robust hop supply chain. The main shared aspects regarding agronomy research for the future in the analyzed new growing areas are the following: Methods of cultivation (e.g., low- vs. high-trellis system, organic vs. conventional farming), irrigation and plant nutrition management, testing of new genotypes to face the climate change effects.

Table 3
State of the art and future targets of agronomic research on hops in the new growing areas.

Growing area	Agronomic practices and growing techniques for hops	
	Adequately referenced	To be studied
Italy	- Screening of commercial cultivars in different environments - Yield and quality potentials of some commercial varieties	- Methods of cultivation (e.g., low- vs. high-trellis system, organic vs. conventional farming) - Soil and irrigation management - Creation and optimization of fertilizer plans according to plant development - Hop plant ideotype in different environmental conditions
Brazil	- Identification of the most suitable commercial cultivars for two-crop-a-year system in tropical and subtropical conditions - Yield and chemical characteristics of cones for different styles of beers.	- Supplemental LED lighting (e.g. type, spectra and quantitative of LEDS per hectare, as well their costs). - Alternatives to control some pests, including fungi diseases and insects and mites, because of the lack of chemical registered for hop cultivation. - Methods of cultivation (e.g. low- vs. high-trellis system) - Fertirrigation methods to increase yield
France	- Conventional hop production in traditional growing areas - Yield and quality potential of main cultivars in historical areas - Pests and diseases management in conventional hop production	- Organic management of hopyard, including pest and disease control - Irrigation monitoring and optimization - Cultivars adaptation, yield and quality references under pedoclimatic conditions of new growing areas - Sustainability of hop production and adaptation to climate change
Virginia (U.S.A.)	- Field testing of existing public-domain cultivars - Disease and pest challenges unique to local growing conditions - Quality attributes of select cultivars as affected by terroir	- Exploration of intensive low-trellis production - Alternative non-brewing markets and uses for hops - Testing of new lines including those from the Hop Breeding Program at NCSU
Florida (U.S.A.)	- Screening of commercial cultivars - Yield and quality potentials of 'Cascade' hops for the double-season production system with photoperiod manipulation - Use of LED lighting	- Trellis design and height - Soil and irrigation management - Cultural practices: planting configuration, fertilization, pruning, etc. - Development of new cultivars with improved yield and quality under subtropical climatic conditions

The hop industry will be dominated by the traditional growing regions for the foreseeable future. However, current trends in precision, and controlled environment agriculture may open avenues for production of high value specialty hops in other parts of the globe. Niche markets for non-traditional hop products and uses may also provide opportunities for individual growers in regions outside the traditional ones. Despite this, it may be hard to justify investment in research and development on hops outside of the main growing regions that currently accounts for nearly 90 % of global hop production.

As a conclusion of this review, in Table 3 were summarized the agronomic aspects already addressed in each new growing area and those that need to be faced in the future.

CRediT authorship contribution statement

Francesco ROSSINI: Writing – review & editing, Writing – original draft, Conceptualization. **Sergio R. Roberto:** Writing – review & editing, Writing – original draft, Conceptualization. **Roberto Ruggeri:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Alessandro J. Sato:** Writing – review & editing, Writing – original draft, Conceptualization. **Perrine Loussert:** Writing – review & editing, Writing – original draft, Conceptualization. **Laban K. Rutto:** Writing – review & editing, Writing – original draft, Conceptualization. **Shinsuke Agehara:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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