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The Global Expansion of Hops: Botanical Characteristics and Historical Evolution in Brewing

Aiping Yu [1], Zefeng Guo [2], Wei Liu [3]
1 Hangzhou Cheerday Brewery Co., Ltd, Chun'an, 311700, Zhejiang, China
2 Enterprise Research Institute, Hangzhou Cheerday Brewery Co., Ltd, Chun'an, 311700, Zhejiang, China
3 Beer Museum, Hangzhou Cheerday Brewery Co., Ltd, Chun'an, 311700, Zhejiang, China
Corresponding author: yuap@qdhbeer.com
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Abstract The cultivation and utilization of *Humulus lupulus* L., commonly known as hops, have significantly evolved, impacting both the brewing industry and botanical research. This study explores the botanical characteristics of hops, emphasizing their secondary metabolites such as terpenes, sesquiterpenes, and prenylated phenolic compounds, which contribute to the bitterness, aroma, and preservative qualities of beer. The historical evolution of hop cultivation is traced, highlighting the genetic and biochemical advancements that have enhanced hop quality and yield. Additionally, the study examines the global distribution of hops and the challenges posed by pests like the hop cyst nematode, which affects hop yield and quality. The integration of modern technologies, such as genomic sequencing and chemometric analysis, has furthered our understanding of hop characteristics and their optimization in brewing. This study underscores the importance of hops in brewing and their potential applications in other industries, driven by their diverse bioactive compounds.
Keywords *Humulus lupulus* L.; Brewing industry; Secondary metabolites; Genetic advancements; Bioactive compounds

1 Introduction

Hops (*Humulus lupulus* L.) have been a cornerstone of the brewing industry for centuries, imparting the characteristic bitterness, aroma, and stability to beer. The female inflorescences, or hop cones, are particularly valued for their rich content of secondary metabolites, including terpenes, sesquiterpenes, and prenylated phenolic compounds, which contribute to the unique flavor profiles and preservative qualities of beer (Natsume et al., 2015; Patzak et al., 2015; Bocquet et al., 2018). The importance of hops extends beyond brewing; they also possess significant medicinal properties, such as antimicrobial, sedative, and estrogenic activities, making them a subject of interest in both the pharmaceutical and agricultural sectors (Bocquet et al., 2018).

The genetic and environmental factors influencing hop quality are complex and multifaceted. Recent advancements in genomic and proteomic analyses have provided deeper insights into the molecular mechanisms underlying the biosynthesis of key compounds in hops. For instance, the draft genome sequences of various hop cultivars have revealed the developmental regulation of genes involved in specialized metabolic processes that impact beer flavor and aroma (Natsume et al., 2015). Additionally, the proteomic mapping of glandular trichomes in hop cones has identified numerous proteins involved in the synthesis and transport of terpenoid-related compounds, further elucidating the biochemical pathways that contribute to hop quality (Champagne and Boutry, 2017).

This study is to explore the botanical characteristics and historical evolution of hops in the context of their global expansion and significance in brewing. By examining the genetic, biochemical, and environmental factors that influence hop quality, this study provides a comprehensive understanding of how hops have been cultivated and utilized across different regions and historical periods. This study will also highlight the advancements in hop breeding and biotechnology that have enabled the development of new hop varieties with enhanced flavor profiles

and agronomic traits. Through a detailed analysis of the historical and contemporary practices in hop cultivation and brewing, this study contributes to the ongoing efforts to optimize hop production and utilization. By integrating insights from genomic, proteomic, and environmental studies, this study will offer valuable perspectives on the future directions for hop breeding and the sustainable development of the brewing industry.

2 Botanical Characteristics of Hops

2.1 Botanical classification and morphological features

Hops (*Humulus lupulus*) belong to the Cannabaceae family and are dioecious, meaning they have distinct male and female plants. The female flowers, known as cones, are particularly valued in brewing for their aromatic and bittering properties. The plant is a perennial climbing bine that can grow up to 7 meters in height. The stems are flexible and covered with rough hairs, which help the plant climb. The leaves are opposite, palmately lobed, and serrated, typically with three to five lobes. The flowers are small and green, with the female flowers forming the characteristic cone shape that contains lupulin glands, which are rich in essential oils and resins (Natsume et al., 2015; Padgitt-Cobb et al., 2021).

2.2 Main chemical components and physiological functions

Hops are renowned for their α-acids and β-acids, which play crucial roles in brewing. α-Acids, such as humulone, are primarily responsible for the bitterness in beer. During the brewing process, these acids are isomerized to iso-α-acids, which impart the characteristic bitter taste. β-Acids, including lupulone, contribute to the preservation of beer due to their antimicrobial properties, although they are less soluble and thus less impactful on flavor compared to α-acids (Natsume et al., 2015; Jacquin et al., 2022).

Hop terpenes, such as myrcene, humulene, and caryophyllene, significantly influence the aroma and flavor profiles of beer. These volatile compounds are responsible for the diverse range of hop aromas, from floral and citrusy to piney and spicy notes. The specific terpene profile of a hop variety can greatly affect the sensory characteristics of the final beer product (Natsume et al., 2015; Jacquin et al., 2022; Xu, 2024).

2.3 Regional varietal differences and ecological adaptability

Hops are cultivated in various regions worldwide, each producing distinct varieties with unique morphological and flavor characteristics. For instance, the Saaz variety, originating from the Czech Republic, is known for its mild, earthy, and herbal aroma, making it a staple in traditional Pilsner beers. The Cascade variety, developed in the United States, is famous for its strong citrus and floral notes, contributing to the flavor profile of many American Pale Ales. The Hallertau variety from Germany is prized for its balanced, mild, and slightly spicy aroma, commonly used in lagers and wheat beers (Natsume et al., 2015; Guimarães et al., 2021; Padgitt-Cobb et al., 2021).

These regional varieties have adapted to their specific ecological conditions, influencing their growth habits and chemical compositions. For example, the Cascade hop has been selectively bred to thrive in the Pacific Northwest's climate, resulting in a robust plant with high resistance to diseases and pests. Similarly, the Saaz hop has adapted to the temperate climate of Central Europe, producing cones with a delicate aroma profile suited to traditional brewing styles (Natsume et al., 2015; Guimarães et al., 2021; Padgitt-Cobb et al., 2021).

3 Historical Evolution and Global Dissemination of Hops

3.1 Early use of hops in Europe

The use of hops in brewing can be traced back to the early Middle Ages in Europe. Archaeological evidence suggests that hops (*Humulus lupulus*) were utilized in beer brewing as early as the ninth century AD in regions such as Germany and the Czech Republic (Behre, 1999; Lukesova et al., 2018). The cultivation of hops began around 859 AD, and by the twelfth century, their value for flavoring and preserving beer was well recognized (Moir, 2000).

In Germany, the significance of hops was solidified by the Bavarian Purity Law (Reinheitsgebot) of 1516, which mandated that only barley, water, and hops could be used in beer production. This regulation not only standardized beer quality but also promoted the widespread cultivation and use of hops in brewing (Moir, 2000). In the UK, however, hops were initially met with resistance and were even condemned as a "wicked and pernicious weed." It wasn't until 1524 that hops were first grown in England, marking the beginning of their acceptance and integration into British brewing practices (Moir, 2000).

3.2 The spread of hops to the Americas and Asia

The dissemination of hops beyond Europe began with the colonization and exploration activities of European powers. Hops were introduced to North America by English and Dutch settlers in the early 17th century. The first hop gardens in North America were established around 1629, and by the 19th century, hop cultivation had spread to various regions, including New York and the Pacific Northwest (Moir, 2000; Kopp, 2014).

In South America, the introduction of hops followed a similar pattern, with European immigrants bringing their brewing traditions and agricultural practices. The spread of hops to Asia occurred later, primarily during the 19th and early 20th centuries, as European colonial powers and traders introduced hops to regions such as India and China. The introduction of hops significantly impacted local brewing industries, leading to the development of new beer styles and the modernization of brewing techniques (Kopp, 2014; Cabras et al., 2023).

3.3 Industrialization and the development of hop cultivation worldwide

The 19th and early 20th centuries saw significant advancements in hop cultivation and brewing technologies. The industrial revolution brought about technological innovations such as refrigeration and pasteurization, which revolutionized the brewing process and enabled the mass production of beer (Cabras et al., 2023). The establishment of scientific breeding programs, such as the one initiated at Wye College in England in 1904, led to the development of improved hop varieties with enhanced disease resistance and brewing qualities (Moir, 2000).

The global expansion of hop cultivation was driven by the increasing demand for beer and the economic benefits of hop farming. By the mid-20th century, commercial hop growing had become established in many temperate regions worldwide, including North America, Europe, and parts of Asia and Oceania (Kopp, 2014). These developments not only transformed the hop industry but also had a lasting impact on modern brewing technologies, allowing for greater control over beer flavor, aroma, and stability (Moir, 2000; Cabras et al., 2023).

The historical evolution and global dissemination of hops have been shaped by a combination of cultural, economic, and technological factors. From their early use in medieval Europe to their spread across continents and the industrialization of hop cultivation, hops have played a crucial role in the development of the global brewing industry.

4 The Role of Hops in Regional Brewing Styles

4.1 Application in traditional European beer styles

Hops have been integral to traditional European brewing styles, significantly influencing the flavor profiles of beers from Belgium, Germany, and the UK. In Belgium, hops are essential in crafting the complex flavors of Belgian Abbey Ales, where they contribute to the balance of sweetness from malt and the fruity esters produced during fermentation. The use of specific hop varieties in these ales imparts subtle bitterness and aromatic qualities that are characteristic of this style (Schönberger and Kostelecky, 2011).

In Germany, hops are a cornerstone of brewing, particularly in the production of lagers and pilsners. The German Purity Law historically mandated the use of hops, which not only provided bitterness but also acted as a natural preservative. The noble hop varieties, such as Hallertau and Tettnang, are renowned for their mild and aromatic properties, which are crucial in defining the clean and crisp taste of German beers (Schönberger and Kostelecky, 2011).

The UK has a rich tradition of using hops in brewing, particularly in styles such as English Bitters. These beers are known for their balanced bitterness and aromatic profiles, achieved through the use of traditional English hop varieties like Fuggle and East Kent Goldings. These hops contribute earthy, floral, and slightly spicy notes, which are essential in creating the distinctive character of English Bitters (Schönberger and Kostelecky, 2011).

4.2 Diversified development of American beer styles

The American craft beer movement has revolutionized the use of hops, leading to the development of a wide array of innovative beer styles. The rise of American IPAs (India Pale Ales) is a prime example, where brewers have experimented with various hop varieties to create intensely hoppy and aromatic beers. American IPAs are characterized by their bold bitterness and vibrant hop aromas, often featuring citrus, pine, and tropical fruit notes (Hopfer et al., 2021; McCabe et al., 2023). The American IPA revolution leveraging the dry-hopping aromas led to the significant boom of the craft beer industry in the last two decades.

Brewers in the United States have embraced dry hopping techniques, which involve adding hops during or after fermentation to maximize aroma without increasing bitterness. This method has been particularly effective in enhancing the aromatic profiles of beers, as demonstrated by the use of hop varieties like Azacca, Idaho-7, and Sultana, which contribute unique and complex aromas to the final product (Figure 1) (Salamon et al., 2022; McCabe et al., 2023). The innovative use of hops in American craft brewing has not only expanded the flavor possibilities but also set new trends in the global beer market.

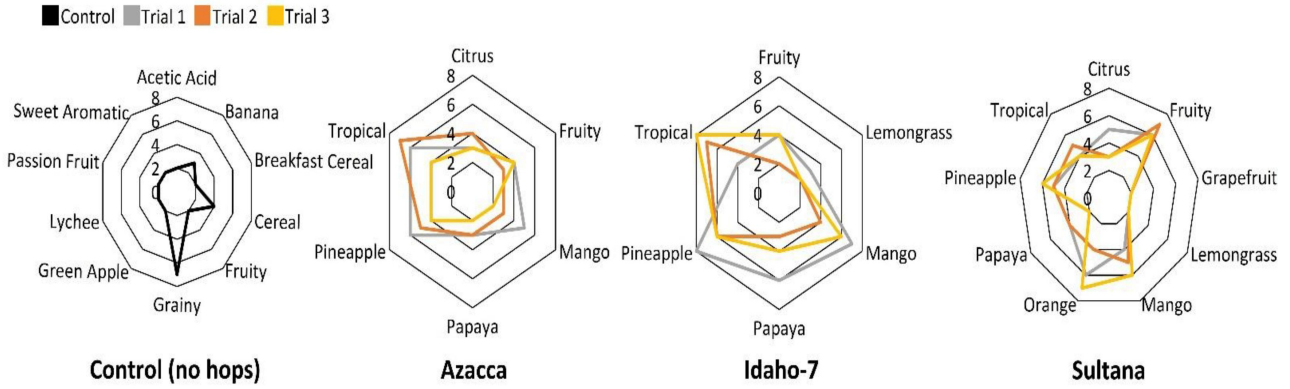

Figure 1 Sensory analysis results using the CATA method on the DraughtLab Pro App (Adopted from McCabe et al., 2023)
Image caption: a control, non-hopped sample (black) and three single-hopped samples hopped with Azacca, Idaho-7, and Sultana each. Hopped sample sensory analyses were conducted in triplicate, wherein each trial was fermented separately (gray, orange, and yellow). Axes numbers represent the number of panelists reporting this aroma (Adopted from McCabe et al., 2023)

4.3 Emerging beer styles in Asia and Oceania

In recent years, the innovative application of hops has also been observed in emerging beer styles in Asia and Oceania. In Japan, craft brewers are increasingly incorporating hops to create unique beer styles that blend traditional Japanese ingredients with modern brewing techniques. The use of hops in Japanese craft beers often results in delicate and refined flavors, with a focus on balance and harmony (Schönberger and Kostelecky, 2011).

Australia and New Zealand have become notable players in the global hop industry, with their hop varieties gaining international recognition for their distinctive characteristics. New Zealand hops, such as Nelson Sauvin and Motueka, are prized for their fruity and tropical aromas, which have been successfully integrated into various beer styles. Australian brewers are also experimenting with local hop varieties to create beers that reflect the unique terroir of the region (Schönberger and Kostelecky, 2011).

The impact of these innovative hop applications in Asia and Oceania is significant, as they not only enhance the flavor profiles of beers but also contribute to the evolution of traditional brewing cultures. By embracing new hop

varieties and techniques, brewers in these regions are pushing the boundaries of beer flavor and creating exciting new styles that appeal to a global audience.

5 Global Hop Production and Supply Chain Analysis

5.1 Major hop-producing countries and their cultivation

The global hop production landscape is dominated by a few key countries, with the United States and Germany leading the charge. These two countries account for roughly two-thirds of the global hop market, with the USA and Germany contributing significantly to both the area under cultivation and total production volumes (Kubeš, 2021). The Czech Republic also plays a crucial role, particularly in the production of aroma hops, holding the third-largest share globally (Šrédl et al., 2020).

In recent years, there has been a notable expansion in hop cultivation in countries like Brazil and Italy, driven by the burgeoning craft beer industry. Brazil, traditionally an importer of hops, has seen a rise in local hop cultivation to meet the demands of its growing number of craft breweries (Figure 2) (Jastrombek et al., 2022; Fortuna et al., 2023). Similarly, Italy has experienced an increase in hop production, particularly in regions like Central Italy and Sicily, where experimental cultivation has shown promising results (Mozzon et al., 2020; Marceddu et al., 2020).

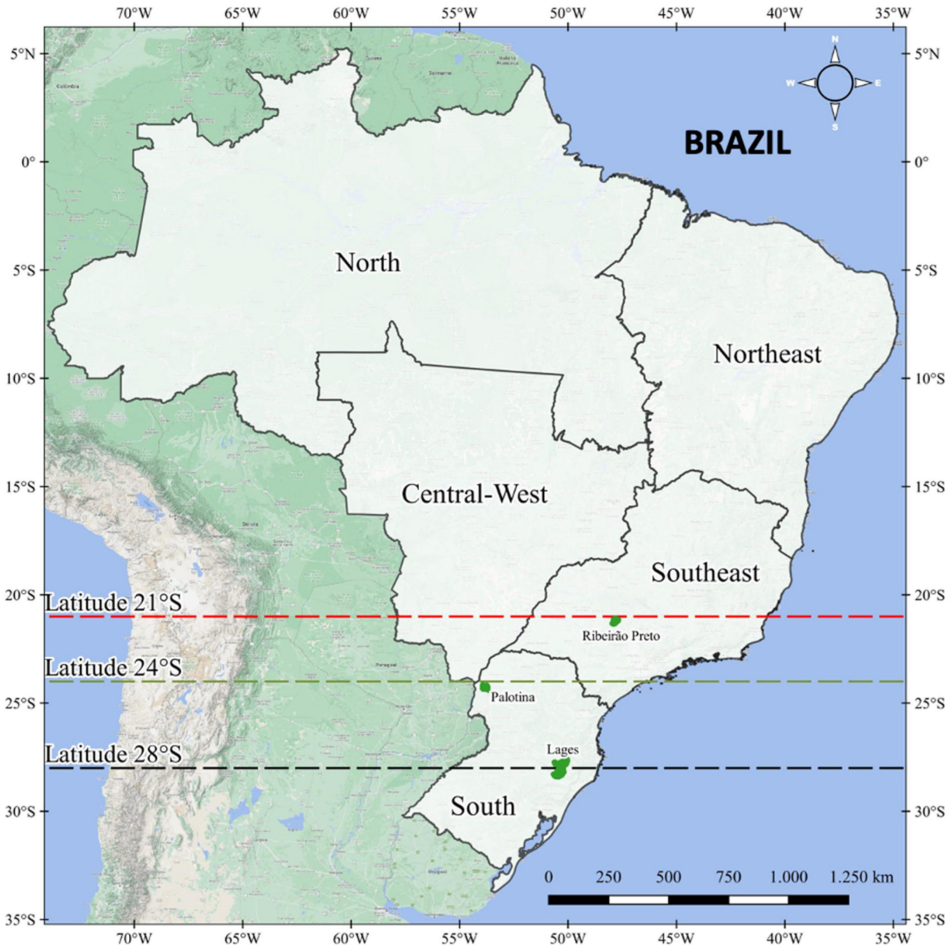

Figure 2 Map of Brazil including some emerging hop-growing areas located at different latitudes (Adopted from Jastrombek et al., 2022)

Image caption: Lages, Santa Catarina state (28° S, 50° W, elevation 916 m a.s.l., Cfb climate, humid subtropical with temperate summer); Palotina, Parana state (24° S, 54° W, elevation 320 m a.s.l., Cfa climate, humid subtropical with hot summer); and Ribeirão Preto, São Paulo state (21° S, 48° W, elevation 516 m a.s.l., Aw climate, tropical with dry winter) (Adopted from Jastrombek et al., 2022)

5.2 Climatic and environmental requirements for hop cultivation

Hops (*Humulus lupulus* L.) are a temperate crop that thrives in regions with specific climatic conditions. The primary environmental requirements for successful hop cultivation include adequate sunlight, moderate temperatures, and sufficient water availability. Hops are typically grown in regions with long daylight hours during the growing season, which is essential for their photoperiodic flowering response (Jastrombek et al., 2022; Fortuna et al., 2023).

In subtropical regions like Brazil, the main challenge is adapting hop cultivars to shorter daylight hours. Techniques such as supplemental lighting and irrigation have been employed to overcome these challenges and optimize yield and quality (Jastrombek et al., 2022; Fortuna et al., 2023). In semi-arid regions, such as parts of Italy, hop cultivation requires careful management of water resources and temperature control to ensure successful growth and high-quality yields (Marceddu et al., 2020).

5.3 Challenges and market volatility in the global hop supply chain

The global hop supply chain faces several challenges, including market volatility, environmental factors, and the need for technological advancements. One of the primary challenges is the fluctuation in hop prices, which can be influenced by changes in demand from breweries, climatic conditions affecting yield, and geopolitical factors (Neve, 1983; Kubeš, 2021). Environmental challenges such as disease, pests, and climate change also pose significant risks to hop production. Organic hop production, for instance, faces difficulties related to weed management, fertility, and disease pressures, which can impact yield and quality (Turner et al., 2011). Additionally, the adaptation of hop cultivars to new growing regions, such as subtropical and semi-arid areas, requires ongoing research and development to ensure successful cultivation (Marceddu et al., 2020; Jastrombek et al., 2022; Fortuna et al., 2023). In recent years, wildfires along the west coast of USA have been impacting the hop quality profile with detectable smoky compounds like guaiacol and cresols that result in smoke taint in the consequent beers.

Market volatility is further exacerbated by the concentration of hop production in a few key countries. Any disruption in these regions, whether due to environmental factors or market dynamics, can have a significant impact on the global supply chain (Kubeš, 2021). The increasing demand for high-quality hops, driven by the craft beer industry, has led to investments in new hop varieties and cultivation techniques to meet the evolving needs of brewers (Dobis et al., 2019; Mozzon et al., 2020; Guimarães et al., 2021).

While the global hop production landscape is dominated by a few key players, there is a growing interest in expanding hop cultivation to new regions. This expansion is driven by the increasing demand from the craft beer industry and the need for diversified raw materials. However, the hop supply chain faces several challenges, including market volatility, environmental factors, and the need for technological advancements to ensure sustainable and high-quality production.

6 Hop Breeding and Future Technological Developments

6.1 Comparison of traditional and modern breeding techniques

Traditional hop breeding methods have relied heavily on phenotypic selection and cross-breeding within established lines to develop new varieties with desirable traits such as improved aroma, bitterness, and disease resistance. These methods, while effective, are time-consuming and labor-intensive, often taking several years to produce a new cultivar (Seigner et al., 2009; Patzak and Henychová, 2018). Traditional breeding has also faced challenges due to the complex genetic architecture of hops, including non-Mendelian inheritance patterns and aneuploidy, which complicate the selection process (Easterling et al., 2018).

In contrast, modern genomic technologies such as molecular breeding, gene editing, and marker-assisted selection (MAS) have revolutionized hop breeding. Techniques like CRISPR/Cas9 have been employed to facilitate precise genetic modifications, enabling the development of strains with specific traits such as enhanced flavor profiles and disease resistance (Krogerus et al., 2021). Genome-wide association studies (GWAS) and quantitative trait loci

(QTL) mapping have identified markers linked to economically important traits, significantly improving the efficiency and accuracy of selection (McAdam et al., 2013; Henning et al., 2019). The draft genome assemblies of various hop cultivars have provided valuable insights into the genetic basis of traits, further aiding in the development of high-quality hop varieties (Natsume et al., 2015; Padgitt-Cobb et al., 2021).

6.2 Future directions in hop variety development

The future of hop breeding lies in the development of new varieties that can meet the evolving demands of the brewing industry and address environmental challenges. One key area of focus is improving disease resistance. By utilizing molecular markers and genomic tools, breeders can develop hop varieties with enhanced resistance to common diseases such as powdery mildew and downy mildew, reducing the need for chemical treatments and promoting sustainable agriculture (Seigner et al., 2009; Henning et al., 2019).

Another important direction is the development of hop varieties with improved stress tolerance. Climate change poses significant challenges to hop cultivation, including increased temperatures and water scarcity. Breeding efforts are now directed towards creating varieties that can withstand these stresses while maintaining high yield and quality (Seigner et al., 2009; Mongelli et al., 2016). Additionally, there is a growing interest in developing hop varieties with unique and enhanced flavor profiles to cater to the craft brewing industry's demand for novel and distinctive beers (Natsume et al., 2015; Krogerus et al., 2021). As the mechanisms of biotransformation become better understood, hop terpenes for citrus notes and thiol compounds for tropical fruit notes in the final beer have been studied in order to develop new cultivars for producing beers with novel flavors.

6.3 Digital agriculture and smart farming technologies

The integration of digital agriculture and smart farming technologies is set to play a crucial role in enhancing hop production efficiency and quality stability. Precision farming techniques, such as the use of drones and satellite imagery, allow for real-time monitoring of crop health and environmental conditions, enabling farmers to make data-driven decisions (Mongelli et al., 2016). Intelligent monitoring systems can track various parameters, including soil moisture, nutrient levels, and pest presence, ensuring optimal growing conditions and timely interventions (Mongelli et al., 2016; Zhu et al., 2024).

Moreover, the application of big data analytics and machine learning algorithms can predict crop performance and identify potential issues before they become critical, further improving yield and quality. These technologies not only enhance the efficiency of hop production but also contribute to sustainable farming practices by minimizing resource use and reducing environmental impact (Mongelli et al., 2016).

In conclusion, the combination of traditional breeding methods with modern genomic technologies and smart farming practices holds great promise for the future of hop cultivation. By continuing to innovate and adapt, the hop industry can meet the challenges of the 21st century and continue to thrive in a rapidly changing world.

7 Functional Compounds in Hops and Their Potential Applications

7.1 Physiological functions of secondary metabolites in hops

Hops (*Humulus lupulus* L.) are renowned for their rich array of secondary metabolites, including xanthohumol, terpenes, and flavonoids, which exhibit significant physiological functions. Xanthohumol, a prenylated flavonoid, is particularly noteworthy for its broad-spectrum biological activities. It has been extensively studied for its antioxidant and anti-inflammatory properties, which contribute to its potential health benefits. Xanthohumol has demonstrated potent cancer chemopreventive activity in vitro, suggesting its role in cancer prevention programs (Stevens and Page, 2004; Yilmazer et al., 2011; Liu et al., 2014). Additionally, xanthohumol has been identified as an effective α-glucosidase inhibitor, indicating its potential in managing hyperglycemia and type 2 diabetes (Liu et al., 2014).

Terpenes, another class of secondary metabolites in hops, are primarily responsible for the characteristic aroma and flavor of hops. These compounds, including alpha-humulene and beta-caryophyllene, also possess anti-inflammatory and antioxidant properties, which further enhance the health benefits of hops (Steenackers et al.,

2015; Hong et al., 2021) Flavonoids, including xanthohumol and its derivatives, contribute to the overall antioxidant capacity of hops, protecting cells from oxidative stress and reducing inflammation (Keukeleire et al., 2003; Mishra et al., 2019). Active hop metabolites have been reported to be effective for human being to fight against virus such as Covid -19 in recent years.

7.2 Applications of hop extracts in functional foods

The development of hop extracts for use in functional foods, beverages, and health products is a burgeoning field. The bioactive compounds in hops, particularly xanthohumol, have shown promise as food additives due to their numerous positive biological effects. Xanthohumol's antioxidant and anti-inflammatory properties make it an attractive ingredient for functional foods aimed at promoting health and preventing disease (Stevens and Page, 2004; Liu et al., 2015).

In the brewing industry, hops are traditionally used for their bittering, flavoring, and preservative properties. However, the potential applications of hop extracts extend beyond beer production. The incorporation of hop extracts into functional foods and beverages can enhance their health benefits, providing consumers with products that support overall well-being. For instance, xanthohumol-enriched beverages could offer antioxidant and anti-inflammatory benefits, while hop-derived terpenes could be used to create functional foods with enhanced flavor and health-promoting properties (Steenackers et al., 2015; Killeen et al., 2017; Hong et al., 2021).

Moreover, the use of hop extracts in health products, such as dietary supplements, is gaining traction. The pharmacological profile of xanthohumol, including its safety and efficacy, supports its potential use as a dietary supplement to promote health and prevent chronic diseases (Yilmazer et al., 2011; Liu et al., 2015). The development of hop-based functional foods and health products represents a promising avenue for leveraging the bioactive compounds in hops to improve public health.

7.3 Medicinal potential and future research directions

The medicinal potential of active compounds in hops, particularly xanthohumol, is a subject of growing interest. Xanthohumol has demonstrated significant anticancer activity, selectively affecting cancer cells and inhibiting key signaling pathways involved in cancer progression. This makes it a promising candidate for cancer prevention and therapy (Jiang et al., 2018). Additionally, xanthohumol's ability to inhibit α-glucosidase suggests its potential in managing metabolic health, particularly in the context of type 2 diabetes (Liu et al., 2014).

The neuroprotective effects of xanthohumol and other hop-derived compounds are also being explored. These compounds have shown potential in protecting neurons from oxidative stress and inflammation, which are key factors in neurodegenerative diseases. Further research is needed to fully elucidate the mechanisms underlying these effects and to develop effective hop-based therapies for neuroprotection (Stevens and Page, 2004; Liu et al., 2015).

Future research directions include the identification and characterization of additional bioactive compounds in hops, as well as the optimization of extraction and formulation methods to enhance their bioavailability and efficacy. Advances in biotechnology and molecular breeding could also play a role in increasing the levels of beneficial compounds in hops, thereby enhancing their medicinal potential (Mishra et al., 2019; Hong et al., 2021).

The secondary metabolites in hops, particularly xanthohumol, terpenes, and flavonoids, exhibit significant physiological functions and hold promise for various applications in functional foods, beverages, and health products. The medicinal potential of these compounds, particularly in cancer prevention, metabolic health, and neuroprotection, warrants further investigation. Continued research and development in this field could lead to innovative hop-based products that promote health and well-being.

8 Sustainable Cultivation and Environmental Impact

8.1 Sustainable cultivation techniques and organic production

The cultivation of hops (*Humulus lupulus* L.) has seen significant advancements in sustainable practices, including organic cultivation, integrated pest management (IPM), and low-input farming techniques. Organic cultivation of hops involves the use of natural fertilizers and pest control methods, avoiding synthetic chemicals. This approach not only reduces the environmental footprint but also meets the growing consumer demand for organic products. Integrated pest management (IPM) is another critical technique that combines biological, cultural, and mechanical practices to control pests with minimal chemical intervention. For instance, the hop cyst nematode (*Heterodera humuli*) is a significant pest in hop cultivation, and effective IPM strategies are essential for managing its impact on yield and quality (Darling et al., 2022).

Low-input farming techniques, which aim to reduce the reliance on chemical inputs, are also gaining traction. These methods include the use of cover crops, crop rotation, and the application of organic mulches to improve soil health and fertility. In Brazil, the adaptation of hop cultivars to local photoperiod conditions has been a major challenge, but the use of supplemental lighting, irrigation, and mulching has shown promise in enhancing yield and quality (Jastrombek et al., 2022). Additionally, the use of biotransformations by yeasts to enhance hop aroma while reducing the amount of hops needed in brewing aligns with sustainable practices by lowering the environmental impact of hop production (Buiatti et al., 2023).

8.2 Environmental impact and climate change adaptation strategies

Climate change poses a significant threat to global hop cultivation, affecting temperature, precipitation patterns, and the incidence of pests and diseases. Warmer temperatures and altered precipitation can impact the growth cycle of hops, leading to reduced yields and quality. For example, higher temperatures and increased land prices have been shown to discourage hop production in certain regions (Dobis et al., 2019). To mitigate these impacts, adaptive strategies are essential.

One such strategy is the development of hop varieties that are more resilient to changing climatic conditions. This includes breeding programs focused on creating cultivars with improved drought tolerance, disease resistance, and adaptability to different photoperiods. In Central Italy, the assessment of various hop varieties under local conditions has provided valuable insights into their suitability for sustainable cultivation (Easterling et al., 2020). Additionally, the use of advanced molecular breeding techniques can help in developing hop strains with desirable traits, such as enhanced flavor profiles and better agronomic performance (Mozzon et al., 2020).

Another important adaptation strategy is the implementation of water-efficient irrigation systems and soil management practices that enhance water retention and reduce erosion. The use of mulching and cover crops can improve soil health and resilience to extreme weather events. In Brazil, the use of irrigation and mulching has been crucial in adapting hop cultivation to the subtropical climate (Jastrombek et al., 2022).

8.3 Policies and management for future sustainable development

The future sustainable development of the global hop industry requires comprehensive policies and management strategies that address environmental, economic, and social aspects. Policymakers need to promote research and development in sustainable hop cultivation practices, including the breeding of resilient hop varieties and the implementation of IPM and low-input farming techniques. Financial incentives and support for farmers adopting sustainable practices can also play a crucial role.

Market strategies should focus on promoting the value of sustainably produced hops, including organic and locally sourced varieties. The growing craft beer industry, which demands unique and high-quality hop varieties, presents an opportunity to drive the market towards more sustainable practices (Machado et al., 2019; Afanasyeva et al., 2023). Additionally, the development of waste-to-resource approaches, such as the conversion of spent hops into valuable nanomaterials, can further enhance the sustainability of the hop industry (Liu et al., 2023).

Environmental management recommendations include the establishment of monitoring systems to track the impact of climate change on hop cultivation and the effectiveness of adaptation strategies. Collaboration between researchers, farmers, and industry stakeholders is essential to share knowledge and best practices. In regions like Brazil, where hop cultivation is emerging, the development of new technologies and practices tailored to local conditions is critical for sustainable growth (Jastrombek et al., 2022).

In conclusion, the sustainable cultivation and environmental impact of hops require a multifaceted approach that integrates organic production, IPM, low-input farming, climate change adaptation, and supportive policies. By adopting these strategies, the hop industry can ensure its long-term viability and contribute to the broader goals of environmental sustainability and climate resilience.

9 Concluding Remarks

Hops (*Humulus lupulus* L.) are dioecious perennial climbing plants primarily known for their use in the brewing industry, where the female inflorescences, or cones, are utilized for their resins and essential oils that impart bitterness and aroma to beer. Historically, hops were first valued for their medicinal properties, being used to treat various ailments such as insomnia, menopausal symptoms, and even cancer. The global expansion of hops has seen them introduced to new regions beyond their native northern hemisphere, including South America, South Africa, New Zealand, and Australia. This expansion has been driven by the growing craft beer industry, which has increased demand for diverse hop varieties and cultivation in non-traditional areas.

The historical evolution of hops in brewing is marked by their transition from medicinal use to a staple ingredient in beer production. The development of hop cultivation practices and the identification of specific hop varieties have been crucial in enhancing the quality and consistency of beer. The genetic study of hops has revealed significant insights into the biosynthesis of compounds responsible for aroma and bitterness, which are essential for brewing. Breeding with new genomic technologies to enhance the flavor compounds and biotransformation precursors will lead to the development of hops with unique features for new product innovation. Despite the advancements, there remains a gap in basic agronomic research, particularly in new growing regions where knowledge and expertise are still developing.

Future research on hops should focus on several key areas to further enhance their agricultural and commercial potential. In agricultural technology, there is a need for more comprehensive studies on hop agronomy, especially in new cultivation regions. This includes developing best practices for both conventional and organic farming to optimize yield and quality. Market development research should explore the economic impacts of expanding hop cultivation to new regions and the potential for new hop varieties to meet the demands of the craft beer industry.

Functional compound studies should delve deeper into the phytochemistry and bioactivity of hops, identifying new compounds with potential health benefits and applications beyond brewing. Sustainable development is another critical area, where research should aim to improve the environmental footprint of hop cultivation through innovative farming techniques and resource management. Additionally, the development of disease-resistant hop varieties through genetic research could significantly reduce the need for chemical inputs, promoting more sustainable agricultural practices.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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