

Research Progress on the Botanical Characteristics and Diversity of *Cannabis*

Shanyu Chen ^{1*}, Wenjun Wang ^{2*}, Sijie Meng ¹, Guanhai Ruan ¹ ✉

¹ Institute of Crops and Nuclear Technology Utilization, Zhejiang Academy of Agricultural Sciences, Hangzhou, 310021, China

² Institute of Industrial Crops, Heilongjiang Academy of Agricultural Sciences, Harbin, 150000, China

* These authors contributed equally to this work

✉ Corresponding author: 13906520484@163.com

International Journal of Horticulture, 2025, Vol.15, No.4 doi: [10.5376/ijh.2025.15.0018](https://doi.org/10.5376/ijh.2025.15.0018)

Received: 01 Jun., 2025

Accepted: 15 Jul., 2025

Published: 02 Aug., 2025

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Preferred citation for this article:

Chen S.Y., Wang W.J., Meng S.J., and Ruan G.H., 2025, Research progress on the botanical characteristics and diversity of *Cannabis*, International Journal of Horticulture, 15(4): 171-184 (doi: [10.5376/ijh.2025.15.0018](https://doi.org/10.5376/ijh.2025.15.0018))

Abstract *Cannabis*, as a highly variable plant, has garnered widespread attention from the scientific community due to its rich cannabinoids (such as THC and CBD) and extensive industrial and medicinal applications. This study systematically analyzes the botanical characteristics and diversity of *Cannabis*, particularly focusing on its taxonomy, genetic diversity, and the pharmacological significance of its chemical components. The research demonstrates that *Cannabis* exhibits significant diversity in its phenotype, genetics, and chemical composition, especially showing complex genetic mechanisms in the biosynthesis pathways of cannabinoids and terpenes. It emphasizes the need for a more precise understanding of the genetic diversity and chemical composition of *Cannabis* through genomics and molecular biology techniques to promote its broad applications in the fields of medicine and industry. This study provides important references for future *Cannabis* research and breeding, as well as theoretical support for its medicinal and industrial applications.

Keywords *Cannabis*; Botanical characteristics; Genetic diversity; Cannabinoids; Medicinal value; Phytochemistry

1 Introduction

Cannabis, a member of the Cannabaceae family, is a highly variable and complex plant species that has garnered significant scientific interest due to its diverse applications and unique chemical composition. The plant produces a distinct class of compounds known as cannabinoids, which include notable substances such as tetrahydrocannabinol (THC) and cannabidiol (CBD) (Chandra et al., 2017; Husnain et al., 2020). The resurgence of interest in *Cannabis* research is driven by its potential medicinal benefits, industrial applications, and recreational use. The plant's ability to adapt to various environmental conditions and its rich phytochemical profile make it a valuable subject for botanical and pharmacological studies (Aliferis and Bernard-Perron, 2020; Strzelczyk et al., 2021).

Historically, *Cannabis* has been utilized for a multitude of purposes. It is one of the oldest known medicinal plants, with documented use in traditional medicine for treating ailments such as asthma, malaria, and skin diseases (Husnain et al., 2020). Additionally, *Cannabis* has been a source of textile fiber and oil production for millennia (Andre et al., 2016; Farag and Kayser, 2017). The psychoactive properties of THC have also led to its widespread recreational use. The dual nature of *Cannabis*, serving both medicinal and recreational purposes, underscores its significance in human history and culture (Pollio, 2016; McPartland, 2018).

Current research on *Cannabis* focuses on several key areas, including its botanical characteristics, genetic diversity, and the pharmacological properties of its constituents. Studies have explored the plant's taxonomy, revealing complexities in its classification and the ongoing debate over the distinction between *Cannabis sativa* and *Cannabis indica* (Pollio, 2016; McPartland, 2018). Advances in genomics and metabolomics have provided deeper insights into the plant's genetic makeup and the biosynthesis of its bioactive compounds (Aliferis and Bernard-Perron, 2020; Kovalchuk et al., 2020). Additionally, there is a growing interest in optimizing *Cannabis* cultivation for pharmaceutical purposes, leveraging its therapeutic potential to develop new treatments for various medical conditions (Chandra et al., 2017; Strzelczyk et al., 2021).

This study provides a comprehensive analysis of the botanical characteristics and genetic diversity of *Cannabis*, with a focus on its taxonomy, phytochemistry, and potential medicinal applications. It also addresses the challenges in *Cannabis* classification, particularly the ongoing debate over species categorization, aiming to bridge the knowledge gaps in *Cannabis* biology and genomics. The study aspires to offer valuable insights for *Cannabis* breeding programs, especially for the optimization and development of cultivars tailored for medicinal and industrial purposes. By deepening the understanding of the genetic and phytochemical complexity of *Cannabis*, the study seeks to promote its efficient and sustainable utilization, supporting its increasingly important role in modern science and industry.

2 Botanical Characteristics of *Cannabis*

2.1 Morphology and plant structure

Cannabis plants exhibit a variety of morphological features that include the root, stem, leaves, and flowers. The root system is typically a taproot, which can extend deep into the soil to anchor the plant and absorb nutrients. The stem is erect and can vary in height depending on the species and growing conditions. Leaves are palmate with serrated edges, and the number of leaflets can vary. The flowers are unisexual, with male flowers forming loose clusters and female flowers forming dense, resinous clusters known as buds (McPartland and Small, 2020; Mazzara et al., 2022; Murovec et al., 2022).

Differences between *Cannabis sativa*, *Cannabis indica*, and *Cannabis ruderalis* are notable. *Cannabis sativa* plants are generally taller with thinner leaves and longer flowering cycles. They are often cultivated for their fiber and seeds. *Cannabis indica* plants are shorter, bushier, and have broader leaves, with shorter flowering cycles. *Cannabis ruderalis* is the shortest of the three, with a more rugged appearance and the unique ability to flower based on age rather than light cycle, a trait known as autoflowering (McPartland and Small, 2020; Roychoudhury et al., 2021; Suárez-Jacobo et al., 2023).

2.2 Phytochemistry

Cannabis plants produce a complex array of phytochemicals, including cannabinoids, terpenes, and other compounds. The primary cannabinoids are delta-9-tetrahydrocannabinol (THC), cannabidiol (CBD), and cannabinol (CBN). THC is the main psychoactive component, while CBD is non-psychoactive and has been studied for its potential therapeutic effects. CBN is a degradation product of THC and is mildly psychoactive (Gonçalves et al., 2020; Radwan et al., 2021; Roychoudhury et al., 2021).

Terpenes are another significant group of compounds in *Cannabis*, contributing to the plant's aroma and potential therapeutic effects. Common terpenes include myrcene, limonene, and pinene. These compounds can interact synergistically with cannabinoids, a phenomenon known as the entourage effect (Radwan et al., 2021; Murovec et al., 2022; Mazzara et al., 2022). Other important phytochemicals in *Cannabis* include flavonoids and alkaloids. Flavonoids contribute to the plant's color and have antioxidant properties, while alkaloids can have various pharmacological effects (Gonçalves et al., 2020; Radwan et al., 2021).

2.3 Reproductive biology

Cannabis plants can be either dioecious or monoecious. Dioecious plants have distinct male and female individuals, while monoecious plants have both male and female flowers on the same individual. This characteristic is crucial for breeding and cultivation practices, as the separation of male and female plants can influence the quality and yield of the crop (Naraine et al., 2019; McPartland and Small, 2020).

Pollination in *Cannabis* is primarily wind-driven, with male plants releasing pollen that is carried to female flowers. Successful pollination results in seed development within the female flowers. Relevant studies have shown that this pollination mechanism is influenced by both biotic and abiotic factors, with pollen transmission affected by environmental conditions such as wind speed and temperature. Female *Cannabis* flowers are rich in cannabinoids, particularly in medicinal *Cannabis*, where chemical compounds like CBD (cannabidiol) and THC (tetrahydrocannabinol) decrease after pollination. After fertilization, the accumulation of cannabinoids and

terpenes in the flowers drops significantly, greatly reducing the medicinal value of pollinated flowers (Feder et al., 2021). Therefore, in commercial cultivation, male plants are typically removed to prevent pollination and ensure the production of seedless, high-THC female flowers, known as sinsemilla.

3 Genetic Diversity and Classification

3.1 Genetic variability within species

Recent advancements in genomics have significantly enhanced our understanding of the genetic diversity within *Cannabis* species. Simple sequence repeat (SSR) markers have been developed and utilized to assess genetic variation and population structure in *Cannabis sativa*. For instance, a study identified 92 409 SSR motifs and developed 63 707 complementary SSR primer pairs, which were used to estimate genetic diversity and population structure, revealing substantial polymorphism and genetic diversity within the species (Zhang et al., 2020). Whole-genome shotgun sequencing has been employed to explore gene copy number variations (CNVs) that influence cannabinoid synthesis and pathogen resistance, providing insights into the genetic mechanisms underlying these traits (McKernan et al., 2020). Reduced representation shotgun sequencing has also been used to identify single nucleotide polymorphisms (SNPs) that can diagnostically classify *Cannabis* varieties, further elucidating the genetic structure of the species (Oultram et al., 2022).

Genetic variability is crucial for the breeding and selection of desirable traits in *Cannabis*. High genetic and phenotypic variability within and among hemp cultivars has been observed, which is beneficial for breeding programs aimed at improving agronomic traits such as flowering time, plant height, and biomass (Trubanová et al., 2023). This variability allows breeders to select for specific traits, enhancing the potential for developing new cultivars with desired characteristics. For example, the identification of genetic markers associated with key traits through genome-wide association studies (GWAS) has provided valuable tools for marker-assisted selection, facilitating the breeding of *Cannabis* varieties tailored for specific medicinal or industrial purposes (Ronne et al., 2023).

3.2 Taxonomic controversies and challenges

The taxonomic classification of *Cannabis* has been a subject of ongoing debate, particularly regarding the distinction between the *sativa*, *indica*, and *ruderalis* varieties. Traditional classifications based on morphological traits have been challenged by molecular evidence. For instance, DNA barcoding has been used to examine the taxonomic classification of *Cannabis*, with findings supporting a unique species system (*C. sativa*) comprising two subspecies: *C. sativa* subsp. *sativa* and *C. sativa* subsp. *indica* (Barcaccia et al., 2020). This molecular perspective suggests that the traditional classification into distinct species may not be as clear-cut as previously thought.

Molecular and genetic studies have provided evidence both supporting and refuting traditional classifications of *Cannabis*. For example, population structure analysis using SSR markers has identified distinct genetic groups within *Cannabis*, which may correspond to traditional classifications based on geographical origins and sexual behaviors (dioecious and monoecious) (Borin et al., 2021). However, other studies have shown that genetic diversity within *Cannabis* does not always align with traditional morphological classifications, indicating that a more nuanced understanding of the species' genetic structure is needed (Kovalchuk et al., 2020). These findings highlight the complexity of *Cannabis* taxonomy and the need for further research to reconcile molecular and traditional classifications.

3.3 Cultivar development and breeding

Hybridization has played a significant role in the development of commercial *Cannabis* strains. A study pointed out that a key issue to address in the breeding process of new *Cannabis* varieties is the taxonomic uncertainty between the two major groups of the *Cannabis* genus, namely Indica and Sativa. Using DNA barcoding technology, the research provided molecular support for a single species system of *Cannabis sativa* and proposed that constructing F₁ hybrids through molecular breeding programs holds great potential (Barcaccia et al., 2020). The results showed that controlled breeding programs to create F₁ hybrids, combining desirable traits from

different parent lines, can result in new varieties with enhanced characteristics (Figure 1). This approach leverages the genetic diversity within the species to produce varieties with higher yields, richer cannabinoid profiles, and stronger resistance to environmental stress.

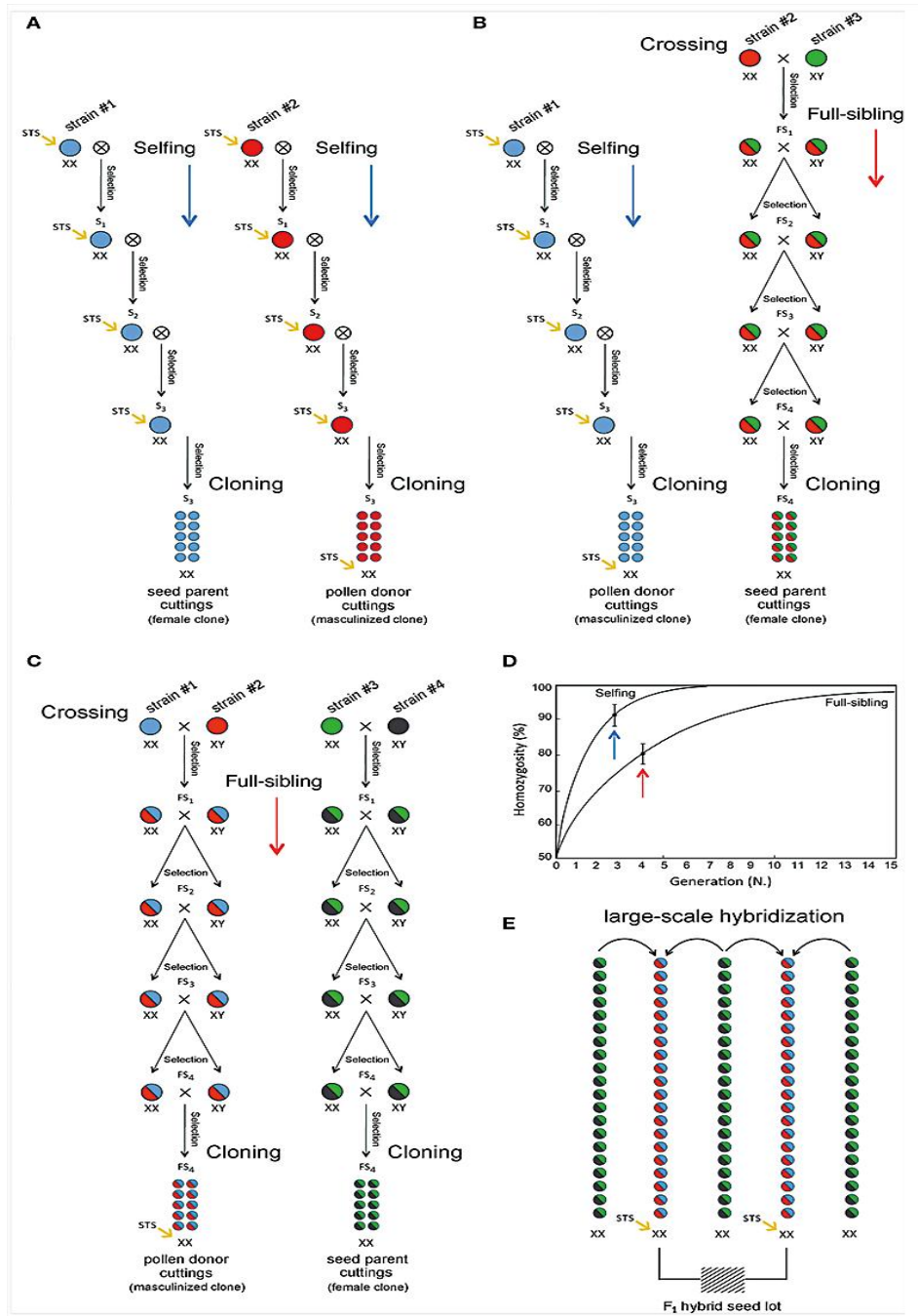


Figure 1 Breeding methods for the development of commercial F₁ hybrid cultivars: two-way (A), three-way (B) and four-way (C) F₁ hybrids with inbreeding progression in case of selfing and full-sibling crosses (D) and large-scale hybridization and F₁ female-seed production (E) (Adopted from Barcaccia et al., 2020)

Image caption: The figure provides a detailed explanation of the processes of selfing and full-sibling crosses, as well as large-scale hybridization and the production of F₁ female seeds. Through these breeding strategies, the figure reveals the advantages of F₁ hybrids, particularly in enhancing plant biomass, growth rate, and fertility through heterozygosity, confirming the key role of heterosis in *Cannabis* breeding. It also emphasizes the process of increasing parental line purity through multiple generations of selfing, which is crucial for maintaining consistency in the variety (Adapted from Barcaccia et al., 2020)

Breeding strategies for *Cannabis* vary depending on the intended use of the plant. For medicinal purposes, breeding programs focus on enhancing the production of specific cannabinoids and terpenes that have therapeutic benefits. For instance, gene copy number variations in cannabinoid synthase genes have been linked to differences in cannabinoid content, providing targets for breeding programs aimed at optimizing medicinal properties (Vergara et al., 2019). In contrast, industrial hemp breeding programs prioritize traits such as fiber quality, biomass production, and resistance to pests and diseases. The development of SSR markers and other genomic tools has facilitated marker-assisted selection, enabling more precise and efficient breeding of *Cannabis* for both medicinal and industrial applications (Zhang et al., 2020; Borin et al., 2021).

4 Environmental Factors Affecting *Cannabis* Growth and Diversity

4.1 Global distribution of *Cannabis* species

Cannabis species are distributed globally, with both wild and cultivated varieties found in diverse environments. The geographic distribution of *Cannabis* is influenced by historical cultivation practices, legal regulations, and environmental conditions. For instance, the phenotypic and chemotypic traits of *Cannabis* can vary significantly based on the region of cultivation, as seen in the comprehensive phenotypic characterization of diverse drug-type *Cannabis* varieties from the Canadian legal market (Lapierre et al., 2023). This study highlights the significant variation in agronomic, morphological, and cannabinoid profiles within a population, which is influenced by the geographic origin and cultivation practices.

4.2 Impact of soil, light, and water

The growth and diversity of *Cannabis* are significantly affected by soil types, lighting conditions, and watering regimes. Different soil types can influence the physiological and metabolic responses of *Cannabis* plants. For example, industrial hemp grown on abandoned mine land soil showed high tolerance to heavy metals and increased cannabidiol content compared to plants grown in commercial soils (Husain et al., 2019). This indicates that soil composition can affect both growth and secondary metabolite production.

Lighting conditions, including light intensity and spectrum, play a crucial role in *Cannabis* growth and cannabinoid production. A meta-analysis identified light intensity, quality, and photoperiod as critical factors influencing *Cannabis* yield and THC accumulation (Backer et al., 2019). Additionally, different light spectra can manipulate secondary metabolism, affecting CBD, CBDA, and terpene concentrations (Reichel et al., 2022). For instance, specific light spectra were found to significantly influence the concentrations of these compounds, demonstrating the potential for optimizing light conditions to enhance desired plant characteristics.

Water availability also impacts *Cannabis* growth and essential oil production. A study conducted in Lebanon revealed that optimal irrigation (Iopt) significantly increased biomass, dry matter, and plant height compared to reduced irrigation (I50) (Sleiman et al., 2022). However, the essential oil content was not statistically affected by the irrigation regime, suggesting that water stress may not always influence secondary metabolite production.

4.3 Climate and geographic distribution

Climate plays a pivotal role in shaping the phenotypic traits and chemotype of *Cannabis*. Environmental factors such as temperature, altitude, and CO₂ concentration are directly related to the yield and stability of phytocannabinoids (Trancoso et al., 2022). For instance, variations in temperature and altitude can influence the growth cycle and cannabinoid profiles of *Cannabis* plants, leading to differences in phenotypic traits.

The geographic distribution of wild and cultivated *Cannabis* varieties is also influenced by climate. Wild *Cannabis* varieties are often found in regions with specific climatic conditions that favor their growth, while cultivated varieties are distributed based on agricultural practices and legal frameworks. The study on the environmental impacts of *Cannabis* cultivation highlights that both indoor and outdoor growing conditions can have significant environmental implications, including water usage, energy consumption, and soil erosion (Zheng et al., 2021). These factors must be considered when evaluating the geographic distribution and sustainability of *Cannabis* cultivation.

5 Advances in *Cannabis* Research Techniques

5.1 Molecular biology and genomics

Recent advancements in *Cannabis* genome mapping have significantly enhanced our understanding of the genetic makeup of *Cannabis sativa*. The relaxation of legislation in certain jurisdictions has allowed for more extensive research into *Cannabis* genomics, leading to the development of key genomic resources. These resources have been pivotal in understanding the basic biology and molecular mechanisms controlling key traits in *Cannabis* (Hurgobin et al., 2020). However, current genome assemblies are still incomplete, with significant portions of the genome missing or unmapped, highlighting the need for coordinated efforts to improve the quality and completeness of these assemblies (Kovalchuk et al., 2020).

Gene-editing technologies such as CRISPR, Zinc Fingers, and TALENs have been explored for their potential in *Cannabis* research. These technologies face challenges due to the highly polymorphic nature of the *Cannabis* genome, which makes precise editing difficult. Nonetheless, *in silico* approaches have been developed to design optimal target sites for genome editing, which could lead to significant advancements in cannabinoid biosynthesis (Matchett-Oates et al., 2021). Additionally, successful CRISPR/Cas9-mediated targeted mutagenesis has been reported, demonstrating the potential for stable gene editing in *Cannabis* (Zhang et al., 2021). These advancements could pave the way for the development of new *Cannabis* genotypes with desirable traits and enhanced secondary metabolite production (Hesami et al., 2021).

5.2 Chemotyping and phenotyping

The analysis of chemical profiles in *Cannabis* has been greatly enhanced by techniques such as Gas Chromatography-Mass Spectrometry (GC-MS) and High-Performance Liquid Chromatography (HPLC). These techniques allow for the detailed characterization of cannabinoid and terpene profiles, which are crucial for understanding the pharmacological properties of different *Cannabis* strains. The use of these analytical techniques has become more prevalent with the increasing legalization of *Cannabis*, leading to the development of large chemotype datasets that can be used to study the gene regulation and pharmacokinetics of cannabinoids (Vergara et al., 2020).

High-throughput phenotyping has emerged as a valuable tool for analyzing various traits in *Cannabis*, including agronomic, morphological, and cannabinoid profiles. This approach allows for the comprehensive characterization of diverse *Cannabis* varieties, providing insights into germination practices, yield, and biochemical diversity. For instance, a study on 176 drug-type *Cannabis* accessions from the Canadian legal market revealed significant variation in traits such as yield, maturity, and THC content, which are essential for precise breeding and cultivar development (Lapierre et al., 2023). High-throughput phenotyping thus plays a crucial role in advancing our understanding of *Cannabis* cultivation and improving the selection of desirable traits for commercial and medicinal use.

6 Case Studies

6.1 Analysis of phytochemical diversity in commercial *Cannabis*

With the acceleration of *Cannabis* legalization in the United States, the variety and uses of *Cannabis* products have become increasingly diverse. *Cannabis* contains various chemical compounds, particularly cannabinoids and terpenes, which have potential medicinal and psychoactive effects (Radwan et al., 2021). Therefore, understanding the phytochemical diversity of *Cannabis* products is crucial for consumer health, safety regulations, and scientific research. However, the labeling systems used in the commercial market, such as "Indica," "Sativa," and "Hybrid," often fail to accurately reflect the true chemical composition of the products, which may mislead consumers.

Smith et al. (2022) analyzed nearly 90 000 samples of commercial *Cannabis* from six states to evaluate the chemical composition variation of *Cannabis* products in the U.S. market. The study found that, although *Cannabis* products are labeled as "Indica" or similar, these labels do not always correspond to their actual chemical composition. Through the analysis of cannabinoid (THC and CBD) and terpene content, the research identified three main chemical types, with THC-dominant products accounting for 96.5% (Figure 2). Furthermore, certain

labels showed biased associations with specific chemical types. The study results reveal the inaccuracy of the current market labeling system and emphasize the need for standardized naming and classification systems to better reflect the true chemical characteristics of *Cannabis* products.

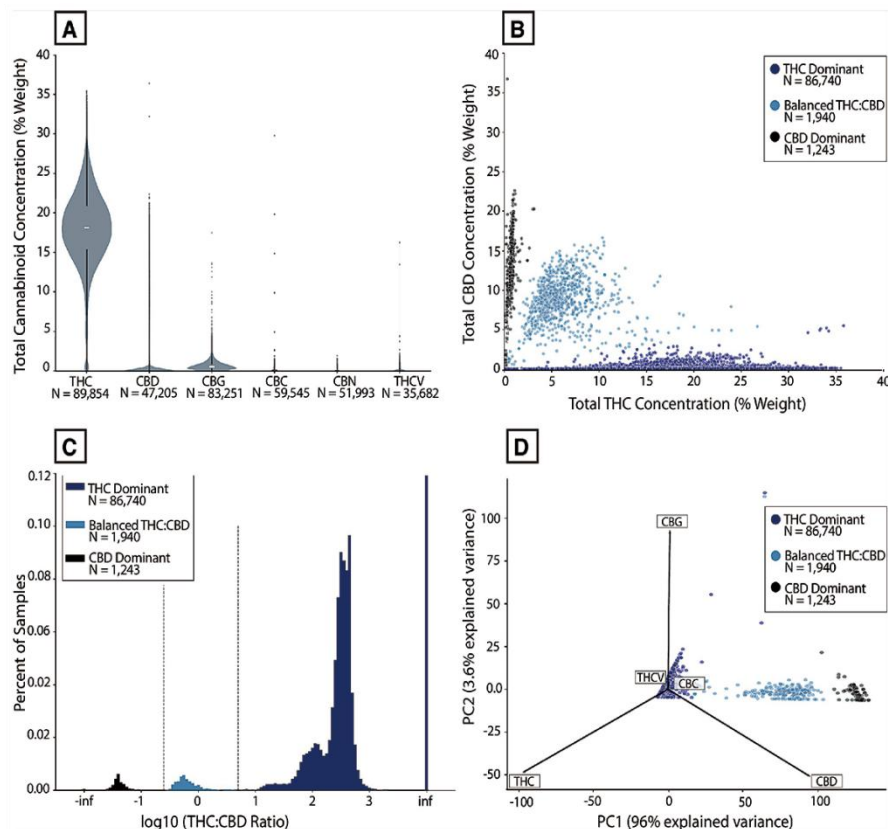


Figure 2 Cannabinoid variation among commercial *Cannabis*-derived product samples in the US (Adopted from Smith et al., 2022)
 Image caption: A: Violin plot of distribution of the set of common cannabinoids measured across all regions; B: Total THC vs. Total CBD levels, color-coded by THC:CBD chemotype; C: Histogram showing THC:CBD distribution on a log₁₀ scale. “Inf” stands for “infinite” (any samples with 0 total THC or CBD); D: Principal Component Analysis of all cannabinoids shown in panel A, color-coded by THC:CBD chemotype (Adopted from Smith et al., 2022)

The figure shows the distribution of total cannabinoid content in commercial *Cannabis* products in the United States, categorized into three main chemical types based on the ratio of THC and CBD (THC-dominant, CBD-dominant, and balanced THC/CBD). The majority of the samples are THC-dominant (96.5%), indicating that the U.S. commercial *Cannabis* market is dominated by products with high THC content. The figure also highlights the concentration differences among cannabinoids, with THC levels significantly higher than other cannabinoids, while CBD and CBG are present at notable levels in only a few samples. These results reveal the high concentration of chemical components in the commercial *Cannabis* market and confirm the market's preference for high-THC products.

6.2 Characterization of key traits in precision breeding of medicinal *Cannabis*

With the renewed recognition of the potential of medicinal *Cannabis*, global demand for it is increasing, particularly in the pharmaceutical sector (Aliferis and Bernard-Perron, 2020). Due to its long-term prohibition, scientific research and breeding efforts related to *Cannabis* have been limited, leading to suboptimal cultivar development and low cultivation efficiency. In recent years, scientists have resumed systematic studies of the physiological traits of medicinal *Cannabis* to advance precision breeding and improve yield and quality.

A study focusing on the characterization of key physiological traits of medicinal *Cannabis* aimed to support precision breeding efforts to enhance yield and optimize cultivation practices. The research cultivated 121

Cannabis genotypes in a controlled environment, analyzed 13 plant parameters, and developed an equation to predict floral bud yield (Naim-Feil et al., 2021). The study found that plant height and stem diameter were positively correlated with yield, while maturation time showed no significant relationship with floral bud production (Figure 3). Additionally, the study identified several traits with high heritability, such as plant height and stem diameter, which can facilitate early selection without completing the full cultivation cycle, thus improving breeding efficiency. The research emphasized the importance of integrating physiological and phenological data into breeding programs, especially for medicinal *Cannabis*, to cultivate scientifically optimized, high-quality varieties for commercial applications.

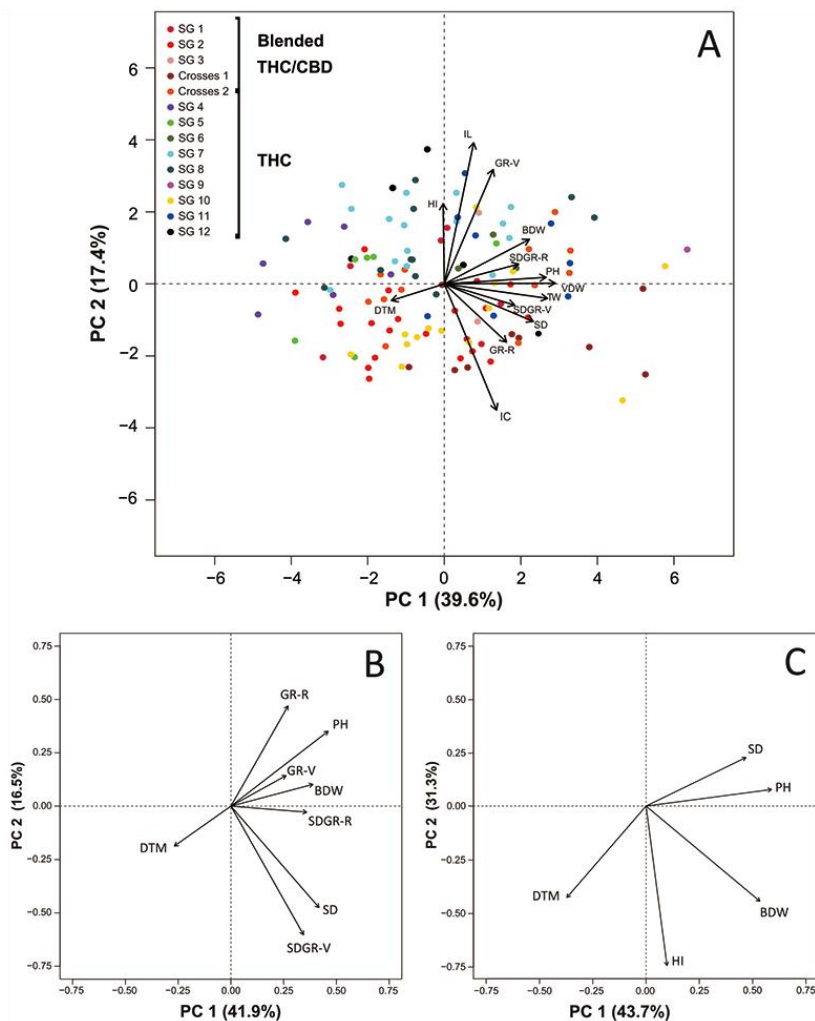


Figure 3 Principle component analysis (PCA) for 121 *Cannabis* lines. A Demonstrates the relationship between 13 physiological traits. Colours indicate plants vernacular classification according to strain groups association (for example, “Purple Kush” or “LA Confidential” strains). Genotypes marked in red (or a variation of red colours) reflect strains with blended THC/CBD ratio while all other colour classify genotypes containing THC and no CBD (cannabinoids profile was estimated by DNA markers). B Shows the associations between growth parameters, DTM and BDW. C Presents the relationship between traits with high breeding values (DTM, HI, BDW, PH, SD) (Adopted from Naim-Feil et al., 2021)

Image caption: The figure reveals the associations between different traits, with two principal components explaining 57% of the phenotypic variation. The analysis shows that days to maturation (DTM) is distinct from other traits and does not exhibit significant correlations, while bud dry weight (BDW) is positively correlated with stem diameter growth rate and plant height. Additionally, the results indicate that genotype classification does not cluster based on vernacular names, suggesting that traditional naming is inconsistent with actual physiological traits. The figure demonstrates that genotype yield predictions can be based on traits like stem diameter and height, emphasizing the importance of phenotypic data in precision breeding (Adapted from Naim-Feil et al., 2021)

6.3 Genetic diversity study of *Cannabis* varieties

In Thailand, with the advancement of *Cannabis* legalization, the "Isara01" *Cannabis* variety has gained increasing attention from the government and research institutions. The Natural Farming Research and Development Center at Maejo University in Chiang Mai conducted genetic research on this variety, aiming to provide scientific evidence for its medicinal value development.

The study utilized RAPD genetic marker technology to analyze the genetic diversity of 133 "Isara01" *Cannabis* plants, revealing genetic differences between groups and their association with chemical compositions (THC and CBD ratios) (Kraisittipanit et al., 2022). Researchers from Maejo University classified the 133 *Cannabis* plants based on genetic fingerprinting, dividing them into four main groups and nine subgroups. The study found that Group D, especially subgroups D1 and D2, had the highest THC-to-CBD ratio, reaching 37:1. This difference indicates that Group D plants hold significant potential for medical applications, particularly for treatments requiring high THC content. The study successfully demonstrated the effectiveness of RAPD markers in classifying *Cannabis* varieties and provided foundational data for future *Cannabis* breeding projects. The results show that the "Isara01" variety exhibits high genetic diversity, making it a valuable candidate for further research and development in Thailand's *Cannabis* industry.

7 Implications for Industry and Medicine

7.1 Medical applications

Cannabinoid diversity plays a crucial role in the therapeutic applications of *Cannabis*. The two primary cannabinoids, Δ^9 -tetrahydrocannabinol (THC) and cannabidiol (CBD), have distinct effects and therapeutic potentials. THC is known for its psychoactive properties, while CBD is non-psychoactive and has been shown to have a range of therapeutic benefits. The combination of these cannabinoids, as seen in nabiximols (a mixture of THC and CBD), has been approved for the treatment of spasticity and neuropathic pain in multiple sclerosis (Cristino et al., 2019; Pagano et al., 2022). Additionally, the endocannabinoid system, which includes cannabinoid receptors (CB1 and CB2), endogenous ligands, and metabolic enzymes, is involved in various physiological processes and is a target for therapeutic interventions in neurological disorders (Cristino et al., 2019; Leinen et al., 2023).

Cannabinoids have been extensively studied for their potential in managing pain, inflammation, and neurological disorders. Preclinical and clinical studies have demonstrated that cannabinoids can modulate pain through various mechanisms, including inhibition of neurotransmitter release, modulation of neuron excitability, and reduction of neural inflammation (Manzanares et al., 2006; Vučković et al., 2018). Cannabinoids have shown promise in treating chronic pain, particularly neuropathic pain, and conditions such as multiple sclerosis and epilepsy (Vučković et al., 2018; Cristino et al., 2019; Sarris et al., 2020). Furthermore, cannabinoids have been investigated for their anti-inflammatory properties, which could be beneficial in treating inflammatory diseases (Manzanares et al., 2006; Bouchet and Ingram, 2020).

7.2 Industrial uses

Different varieties of *Cannabis* have significant potential for various industrial applications. *Cannabis sativa*, for instance, is known for its high fiber content, making it suitable for producing textiles, paper, and building materials. The seeds of *Cannabis* plants are rich in oil, which can be used in food products, cosmetics, and biofuels. The versatility of *Cannabis* varieties extends to their use in producing biodegradable plastics and other sustainable materials, highlighting the plant's potential in contributing to a circular economy (Pagano et al., 2022; Leinen et al., 2023).

7.3 Challenges and future directions

One of the primary challenges in *Cannabis* research is the regulatory and legal barriers that restrict the cultivation, distribution, and study of *Cannabis* and its derivatives. These restrictions have historically limited the scope of research and the availability of high-quality clinical data. The legal status of *Cannabis* varies widely across

different regions, complicating international research collaborations and the development of standardized therapeutic protocols (Abrams, 2018; Black et al., 2019).

There is a pressing need for standardization in the identification of *Cannabis* cultivars and quality control of *Cannabis* products. Variability in cannabinoid content and the presence of contaminants can affect the safety and efficacy of *Cannabis*-based therapies. Establishing standardized methods for cultivar identification, cannabinoid profiling, and quality assurance is essential to ensure consistent and reliable therapeutic outcomes. This standardization will also facilitate regulatory approval and acceptance of *Cannabis*-based medicines (Legare et al., 2022; Leinen et al., 2023). While the therapeutic and industrial potential of *Cannabis* is vast, addressing regulatory challenges and establishing robust quality control measures are critical for the advancement of *Cannabis* research and its applications in medicine and industry.

8 Future Directions and Research Gaps

8.1 Areas requiring further research

Despite significant advancements in *Cannabis* research, several areas still require further investigation. One critical gap is the comprehensive understanding of *Cannabis* genetics and the expression of key traits. Years of prohibition have left the research community undersized and with limited knowledge about *Cannabis* genetics and trait inheritance (Lapierre et al., 2023). Additionally, the current *Cannabis* genome assemblies are incomplete, with significant portions missing or unmapped, highlighting the need for a coordinated effort to quantify the genetic and biochemical diversity of this species (Kovalchuk et al., 2020). Furthermore, the pharmacological properties and biosynthetic pathways of cannabinoids, such as THC and CBD, have been extensively studied, but the molecular mechanisms and potential therapeutic applications of other cannabinoids and terpenoids remain underexplored (Hernández and Chandra, 2016).

8.2 Potential technological advancements in *Cannabis* studies

Technological advancements hold great promise for accelerating *Cannabis* research. Modern genomics technologies, such as molecular markers, microRNA, and omics-based methods, can significantly enhance our understanding of *Cannabis* biology and facilitate genetic improvement (Hurgobin et al., 2020; Hesami et al., 2020). The application of these technologies can help overcome species-specific challenges, increase productivity, and improve the quality of *Cannabis* products. Additionally, the use of light-emitting diodes (LEDs) in *Cannabis* cultivation has shown potential to improve growth and reduce energy requirements, which could be further explored to optimize yield and cannabinoid content (Backer et al., 2019). The biotechnological production of cannabinoids through transgenic approaches also presents a promising avenue for future research.

8.3 Policy and regulation impacts on *Cannabis* research

The legal and regulatory landscape surrounding *Cannabis* has a profound impact on research progress. Historically, the Single Convention on Narcotic Drugs of 1961 restricted *Cannabis* research, but recent legislative changes in various jurisdictions have relaxed these constraints, allowing for more extensive scientific exploration (Hurgobin et al., 2020). However, the rapidly changing cultural, political, and legal environment still poses challenges. There is a need for innovative research designs to bridge the gap between *Cannabis* use and empirical data, which is crucial for informing public policy, medical decision-making, and harm reduction approaches (Hutchison et al., 2019). Additionally, the removal of barriers such as the Public Health Service (PHS) Review, which has inhibited government funding and access to research samples, is essential for advancing our understanding of *Cannabis* and its potential benefits (Hernández and Chandra, 2016).

9 Concluding Remarks

The research on the botanical characteristics and diversity of *Cannabis* has revealed significant insights into its phenotypic, genetic, and biochemical diversity. Studies have shown extensive variation in traits such as yield, maturity, and cannabinoid profiles among different *Cannabis* accessions, which are crucial for breeding and cultivar development. The presence of a wide array of non-cannabinoid compounds, including flavonoids and terpenes, has been highlighted, suggesting their potential synergistic effects with cannabinoids. Genomic studies

have identified gaps in current genome assemblies, emphasizing the need for more comprehensive genomic resources to support *Cannabis* research and breeding. Additionally, the historical and ethnopharmacological significance of *Cannabis* has been well-documented, underscoring its medicinal and recreational use.

Future research should focus on closing the gaps in *Cannabis* genomics to enable precise breeding and cultivar development. This includes improving genome assemblies and mapping genetic diversity more accurately. There is also a need to explore the pharmacological potential of non-cannabinoid compounds and their interactions with cannabinoids, which could lead to the development of more effective therapeutic applications. Furthermore, understanding the physiological and phenological traits that influence productivity and cannabinoid profiles can aid in the selection of high-yielding and disease-resistant cultivars. The integration of modern genomics technologies with traditional breeding methods holds promise for accelerating the genetic improvement of *Cannabis*.

The botanical study of *Cannabis* has made significant strides, but much remains to be explored. The plant's complex genetic makeup and diverse chemical profile present both challenges and opportunities for researchers. By leveraging advanced genomic tools and fostering interdisciplinary collaborations, the scientific community can unlock the full potential of *Cannabis* for medicinal, industrial, and agricultural applications. Continued research and a deeper understanding of this versatile plant will not only enhance its utility but also contribute to its acceptance and integration into modern science and society.

Acknowledgments

We sincerely thank Professor Qi Xingjiang of Zhejiang Academy of Agricultural Sciences for his help and support in this project, would also like to extend my sincere thanks to two anonymous peer reviewers for their thorough assessment and constructive comments, which have all contributed significantly to the improvement of this manuscript.

Funding

This paper was funded by the project "Construction of precision Breeding Facilities for Industrial Hemp" (10402110120AP2201F) funded by the special financial fund of Zhejiang Academy of Agricultural Sciences.

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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