



Review

# A Review on the Current State of Knowledge of Growing Conditions, Agronomic Soil Health Practices and Utilities of Hemp in the United States

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**Abstract:** Hemp (*Cannabis sativa* L.) is an emerging high-value specialty crop that can be cultivated for either fiber, seed, or cannabidiol (CBD). The demand for hemp and its products has been consistently on the rise in the 21st century. The United States of America (USA) has reintroduced hemp and legalized its production as an agricultural commodity through the 2018 Federal Farm Bill. Although there is a renewed interest in the adoption of hemp due to the emerging market, its production in the United States (US) remains limited partly because of unclear agronomic guidance and fertilization recommendations. This review article provides information on the current agronomic management practices that are available in the literature and identifies the future research needs for cultivating this multipurpose crop to address the growing market demands. Hemp production could be beneficial if managed properly. Hemp fertilizer requirements vary in accordance with the type of hemp grown (seed, fiber, or CBD), soil, environmental conditions and requires a wide range of macro- and micronutrients. Integrating management practices in hemp cultivation intended to build soil health is promising since the hemp cropping system is suitable for crop rotation, cover cropping, and livestock integration through animal waste applications. Hemp also has significant environmental benefits since it has the potential to remediate contaminated soils through phytoremediation, convert high amounts of atmospheric CO<sub>2</sub> to biomass through bio-sequestration, and hemp biomass for bioenergy production. This review identifies that most of the agronomic research in the past has been limited to hemp fiber and, to some extent, hemp seed but not CBD hemp. With the increase in the global markets for hemp products, more research needs to be conducted to provide agronomic guidelines for sustainable hemp production.

**Keywords:** Cannabis; hemp CBD; hemp fiber; hemp oilseed; soil health for hemp; agronomic management practices

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## 1. Introduction

Industrial hemp (*Cannabis sativa* L.) or hemp production has recently been the subject of increasing interest around the world, especially in the United States. Hemp is not only a crop that is among many possible agricultural products that could supplement or replace fiber or paper, but it is also a crop with environmental benefits and a potentially profitable crop that fits into sustainable farming systems [1]. Hemp is one of the world's oldest cultivated plants that was developed from wild *Cannabis* plants that originated most probably in Central Asia over 3000 years ago [2]. It is a multipurpose crop that could also be grown for its seed, oil, food, and medicinal properties. Hemp is a dioecious annual wind-pollinated crop with separate male and female plants, and occasionally monoecious. It is also a short-day and photoperiod sensitive crop. Differences in growth rate and development between male and female plants are typically evident since the male plants tend to flower and senesce earlier [3].

Marijuana and hemp belong to the same plant species (i.e., *Cannabis sativa*). However, hemp is genetically different and also distinguished by its use and chemical makeup. More than 100 different chemical compounds called cannabinoids can be extracted from hemp. Two major cannabinoids are tetrahydrocannabinol (THC) and cannabidiol (CBD). Hemp contains THC of 0.3% or less, while marijuana can contain up to 20% THC, as its primary psychoactive chemical. Certain varieties of hemp have higher levels of CBD, the non-psychoactive part, has medicinal properties [4]. A high ratio of CBD to THC would make hemp very relevant as a medical treatment for ailments, but opinions remain mixed about how CBD levels might influence the psychoactive effects of THC [4].

The interest in hemp and its benefits has spurred since significant changes in the legalization of hemp in the USA [5]. For decades, federal law did not differentiate hemp from other *Cannabis* plants. *Cannabis* of any kind was made illegal and hemp was classified as a Schedule I Controlled substance according to the Controlled Substance Act of 1970. There was no large-scale industrial production in the US, and the US market was mainly dependent on imports both as finished hemp products and as ingredients for use in further processing [4]. The USA was the biggest importer of hemp products [4], obtaining most of its seed and fiber from Canada and China, respectively. In 2014, the United States Congress granted permission through the Farm Bill to run test programs for growing hemp in a number of US states. Since then, 41 states have passed legislation that allows hemp cultivation. The 2018 Farm Bill declassified hemp from the list of controlled substances and legalized the production of hemp as an agricultural commodity [5]. According to the 2018 Farm Bill, hemp that is allowed to be cultivated should have a THC threshold of 0.3%. The US Drug Enforcement Administration (DEA) sternly controls its production and enforces rules governing the conditions under which hemp must be cultivated. Any hemp crop found to have THC levels beyond 0.3% must be disposed of accordingly as it is classified as marijuana under the Controlled Substances Act [6]. Currently, over 30 nations grow hemp as an agricultural crop and sell on the world market. Hemp's global market is predicted to double from the year 2016 to 2020, and at present, the US is the third-largest producer of hemp. Currently, hemp production is legal in 46 states in the US and it is cultivated for commercial or research purposes in at least 47 countries in the world. In the US, the amount of hemp acreage and licenses has increased rapidly in the last couple of years.

Due to an increase in demand for non-food crops and other food derivatives in the agricultural sector, hemp has progressively recovered its importance [7]. Hemp is an unconventional crop with a broad spectrum of adaptation throughout North America [8]. The diverse range of products that a hemp plant could produce has drawn the attention of a variety of industries. These include agriculture, textile, automotive, construction, bio-fuel, oil, cosmetics, pharmaceutical industry, etc. [9]. Due to this increase in interest in hemp cultivation for multipurpose production, some dual-purpose hemp varieties were also introduced in European countries that yield both fiber and seed [10].

Hemp has the potential to be an environmentally friendly and highly sustainable crop if managed properly [11]. Hemp replenishes the soil and has been proven to remediate contaminated soils [12–14]. Generally, it is considered as a crop that could be grown without any pesticides [15] for certain varieties [16]. Hemp has the potential to suppress weeds efficiently and can fit well in a crop rotation [17]. Additionally, some residues of hemp can be used as botanical insecticides, miticides, or repellants within programs of pest management in organic farming [18]. These properties also make it suitable for integration in an organic farming system. The United States Department of Agriculture (USDA) policy on organic certification of hemp states “For hemp produced in the United States, only hemp produced in accordance with the US Domestic Hemp Production Program and/or the 2014 Farm Bill may be certified as organic, if produced in accordance with USDA organic regulations” [19]. Hence, the advantages of this crop in agriculture are not exclusively limited to its wide range of products and applications, but also due to its potential to improve soil health that encompasses the plant, environmental, and human health components. The overall aim of this review is to (1) provide the current state of knowledge and agronomic management practices involved in growing hemp for fiber, seed, and CBD, and (2) to identify the research needs to improve sustainable hemp production.

## 2. Hemp Commercial Utilities and Environmental Benefits

### 2.1. Multipurpose Hemp Crop and Potential Markets

#### 2.1.1. Hemp Grown for Fiber

Fiber derived from hemp is one of the strongest and durable forms of natural fiber. Hemp grown for fiber is one of the oldest and most widely cultivated varieties of hemp. Back in the late 19th and early 20th centuries, other natural fibers and synthetic fibers competed for hemp's uses as a textile fiber [20]. Currently, hemp has been re-discovered as a sustainable [21], high yielding industrial fiber crop [22] that can help meet the high global demand for fibers. Harvesting for fiber involves mowing (often by a sickle-bar mower), retting in the field, and baling [23]. Hemp fiber is used for textiles, clothing, as biocomposites for automobiles, paper, building materials (hempcrete), animal bedding, and has potential as a bio-fuel crop too [8]. Hemp consists of two types of fibers namely (1) long outer fibers, referred to as bast and (2) the inner short fibers called hurd [24]. For thousands of years, hemp was grown for its bast fiber, while the hurd was regarded as a waste by-product of bast production. Bast fibers can account for 20–30% of the stalk, and superior quality bast fiber is obtained from hemp fields that are densely planted. Hurd fibers, on the other hand, make up 70–80% of the stalk and typically contain 20–30% lignin [25]. Microbial, chemical, or mechanical means are used to separate the fibers from non-fiber components, or the more valuable bast from the hurds [23]. However, each type of fiber has its use in the industry. Bast are generally used in the automotive and the paper industry, while hurd is primarily used as a livestock bedding, and other construction applications including fiberboard [26]. Fiber produced by dual-purpose varieties is believed to be of lower quality than that produced by traditional fiber varieties. However, the economic benefits of using the whole plant (i.e., including fiber and seed production) may outweigh this factor. Fiber varieties are typically harvested during flowering but before seed formation to obtain optimal fiber quality [27]. Agronomic management practices and growing conditions such as plant density, nitrogen (N) fertilization, and harvest time are important factors that affect yield and quality of fibers [9,28] and are discussed further in this review.

#### 2.1.2. Hemp Grown for Oilseed or Hemp Oil

For at least 3000 years, hemp seed has been used by both humans and animals directly as a food ingredient or crushed for oil and livestock feed [29]. Hemp seed oil or hemp oil was also used as lighting oil, and for making soap, paints, and varnishes. Studies have been reported on the uses of hemp in food, beverages, and medicinal preparations, or it being used as a bird and fish feed [30]. The soft seed meal produced by hulling differs from the press-cake that remains after the seed oil has been extracted, which also has been referred to as seed meal [26]. Nowadays, hemp seed can be made into flour, just like soy, that contains the right amount of protein for the vegetarian diet. The powder, which is characterized by a nutty flavor, adds a unique culinary and healthy twist to baking. In addition to the nutritional values derived from hemp seed, it has positive health benefits, including reducing cholesterol and high blood pressure [31].

Hemp seed is rich in essential and unsaturated fatty acids, and contains as much protein as soybean. The seeds contain approximately 30% protein which includes eight of the daily essential amino acids recommended for humans, 25% starch, and 30% oil [31]. Hemp seed oil is rich in omega-6 and omega-3 essential fatty acids, and is considered ideal for human health [32,33]. Hemp seed oil contains high quantities of linolenic acid and antioxidants of dietary significance [31]. Oil produced from crushed hemp seed is an ingredient in a large variety of body-care and skin products, e.g., shampoos, soap, cream and hair conditioner, industrial oils, and nutritional supplements.

Economic prospects for a hemp oilseed crop in the United States is promising, as the demand for hemp seed products (seed, oil, and press-cake) is steadily increasing [34]. Besides the fact that hemp seed oil has various advantages over other vegetable oils, the present health awareness has made it

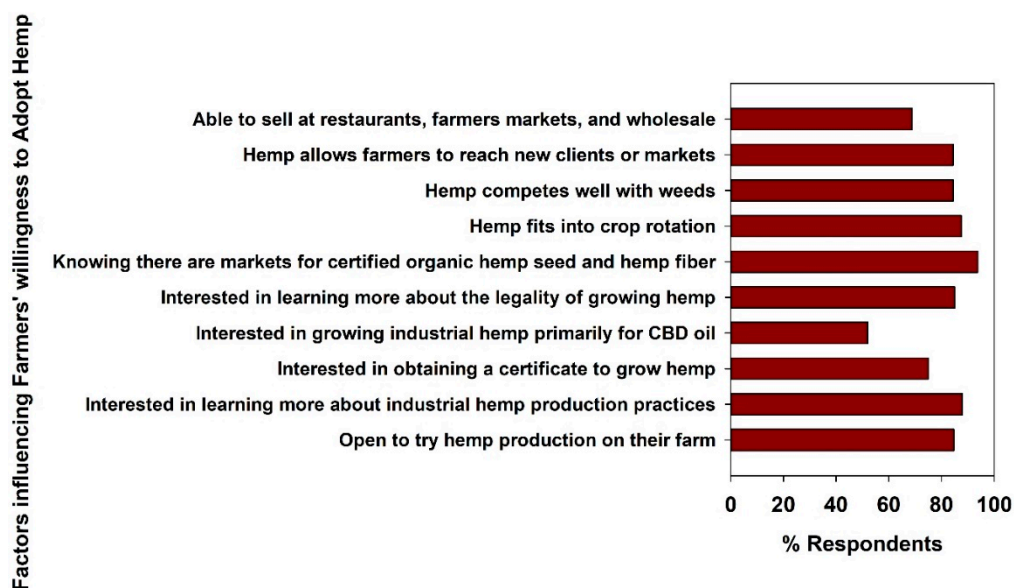
essential to characterize additional vegetable oil sources, e.g., hemp, to be explored as specialty oils. Hence, currently, there is a great deal of focus on the possibility of exploiting this new crop for seed and oil production [35].

### 2.1.3. Hemp Grown for CBD

*Cannabis* contains a special class of terpenophenolic compounds—the cannabinoids. CBD, the principal cannabinoid of hemp and a non-psychoactive component extracted from the hemp plant, is one of these compounds. CBD was first extracted from *Cannabis* in the late 1930s [36] and has ever since been found to have the curative potential for disorders like inflammation and anxiety as well as a potential neuroprotective agent and an antioxidant [36,37]. The other cannabinoid of interest in *Cannabis*, which is reported to have psychoactive property, is THC. It is the most abundant of over 60 different cannabinoids. Marijuana primarily produces THC, while hemp varieties produce CBD. However, legally, any *Cannabis* plant with a THC content at or below 0.3% is regarded as hemp, and above this limit is marijuana. Over the years, CBD also has been tested to treat arthritis, cancer, diabetes, neurodegenerative diseases, and pain [38]. The US Food and Drug Administration (FDA) recognizes the potential of CBD in the development of therapies but is committed to improving the regulatory pathways for lawful marketing intended to ensure consumer health and safety. The CBD has been reported to alleviate the intoxicant effects of THC but it is highly debatable and still being intensely studied [39].

Hemp varieties grown for CBD are different from the seed or fiber producing varieties. Since CBD is mainly concentrated in female flowers, the plants are often started in greenhouses from propagated female clones and are transplanted two to four weeks after establishment. The use of hemp for generating CBD has not received much consideration as of now, although there is a growing commercial interest in using hemp plants for this purpose [35]. CBD has been an emerging area of interest in the United States since hemp was legalized, and most states have started passing laws that will enable more farmers to produce CBD. Apart from its various health benefits, it is an ideal crop especially for small scale limited resources farmers who are interested in cultivating hemp for CBD. CBD is believed to be much more economical than all other hemp by-products, and its sales are estimated to lead all other hemp-based products by 2022 [40].

Even though there is a knowledge gap in hemp cultivation for CBD, many farmers across the United States are looking to grow CBD hemp. A study published on a recent survey suggested that there is an interest among farmers to adopt hemp due to the growing market for hemp products mainly CBD [41]. Specifically, this study involved the participation of a total of 245 organic farmers in North Carolina who participated in an online Qualtrics questionnaire to ascertain their knowledge of, and willingness to adopt, hemp cultivation. Findings from this study revealed that a majority of respondents (85%) of North Carolina organic growers are interested in growing hemp on their farms and the majority showed interest in learning more about crop production practices, varieties, and legality associated with growing this crop (Figure 1). Among the respondents, about 52% wanted to grow hemp primarily for medicinal CBD production. More research needs to be conducted to test CBD hemp varieties under different growing conditions to produce higher CBD concentrations while keeping the THC levels below the legal limit of 0.3%. It is expected that this interest will further improve once specific agronomic guidelines for growing CBD hemp has been established.



**Figure 1.** Factors influencing farmers' willingness to adopt hemp through a survey study conducted in North Carolina. Adapted from [41].

## 2.2. Environmental Benefits

### 2.2.1. Phytoremediation

Hemp is recognized as one of the plants that could be used for land reclamation due to its intense growth specifically for the high yielding fiber varieties [42]. Hemp has been shown to have an intrinsic capacity for phytoremediation, remediating land polluted by heavy metals [43]. The hemp grown for fiber is tall, and its roots grow deep into the soil about 45–90 cm. This enables the plant root to penetrate deep and increase the efficiency of removing widespread contamination as compared to other plants with a shallow root system [13]. Hemp has a high potential to absorb and accumulate heavy metals like lead (Pb), nickel (Ni), cadmium (Cd), etc., through its roots and then store them, thus, making it possible to harvest the hemp plant alongside the hazardous compounds. A wide range of hemp varieties are good candidates for phytoremediation and they have a high tolerance to Cd stress [44]. The same study also found that the highest concentrations of heavy metal accumulations were found in the leaves, although they were distributed in every part of the plant. Leaves of hemp plant collected from a contaminated heavy metal site in Pakistan showed an accumulation of heavy metals; Cu ( $1530 \text{ mg kg}^{-1}$ ), Cd ( $151 \text{ mg kg}^{-1}$ ), and Ni ( $123 \text{ mg kg}^{-1}$ ), respectively [45]. Back in 1986, hemp was planted to help decontaminate the soil around the site where the Chernobyl Nuclear Disaster occurred [13].

### 2.2.2. Carbon Sequestration

Hemp's fast growth and development makes it one of the fastest sources of  $\text{CO}_2$ -to-biomass converter. Hemp has been proven to be an ideal carbon sink as it can capture more  $\text{CO}_2$  per hectare than other commercial crops or even forests. For example, one hectare of hemp can absorb 22 tons of  $\text{CO}_2$  per hectare. High biomass crops like hemp, that are grown for fiber, can sequester higher amounts of carbon by photosynthesis and then store it in the plant's body and roots through bio-sequestration. Most of the carbon is stored in the harvested hemp stem and less in the roots and leaves. Hemp could produce at least 13 tons of biochar per hectare annually [46]. One of the other potential uses of hemp biomass would be the production of biochar for soil applications that could potentially improve soil carbon sequestration and reduce greenhouse gas emissions [47,48].

### 2.2.3. Biomass and Bioenergy

Hemp has been recognized as one of the energy plants due to its high biomass and energy concentration per hectare [49]. Weed suppressing abilities, low pesticide requirements, and soil health improvement properties of hemp plants make it even more energy efficient [49,50]. Fuel properties of hemp are either similar or superior to other solid biofuels such as cereal straw, wood, etc. [51]. For example, the heat of combustion of hemp (18.4–19.1 MJ/kg) is comparable to maize *Zea mays* (18 MJ/kg), slightly greater than Jerusalem artichoke *Helianthus tuberosus* (16.5 MJ/kg), and slightly less than *Miscanthus* sp. (19.8 MJ/kg) [50–52]. Additionally, both wet and ensiled hemp biomass can be transformed into biogas and ethanol [49,52]. Hemp also emits comparatively low sulfur compounds [50] and has low ash content [49]. Thus, hemp has the potential to contribute toward renewable energy.

## 3. Growing Conditions for Hemp Cultivation

### 3.1. Soil Conditions

Hemp can be grown on several soil types, but it thrives best on loose, well-drained loam soils that are rich in organic matter [53,54]. The most suitable soil for hemp cultivation should have a pH 6.0–7.5 [28] and according to [55], the optimum soil pH for hemp production ranges between 5.8 and 6.0 as it does not grow well in acidic soil. The soil should be deep, well-aerated, rich in nutrients, and have a good water-holding capacity [53]. Sandy loam texture is ideal for hemp growth, followed by clay loam, but heavy clay soil and sandy soil are not very well suitable because they hold too much or too little water [56]. Soil preparation is an essential process in hemp cultivation, and all soil hard pans should be broken to allow free draining as waterlogging kills the plants, especially the young ones. The presence of a compacted layer can restrain root development, particularly when the compaction pan is due to poor soil preparation. Hemp is a tap-rooted crop, and in fine soils, the taproot typically takes on an L-shape, which negatively affects the uptake of nutrients and water by the crop [15]. A study concluded that fertile clay loam or silt loam soils with neutral alkalinity are most suitable for hemp cultivation [57]. Hemp does not germinate well in acid sandy soils, heavy clay, or gravelly soils. Hemp plants could grow in peaty marshlands but will yield lower amounts and quality of fiber [57]. Hemp is very sensitive to soil moisture conditions and should not be subjected to drought. It grows well in soils with high water-holding capacity, and good soil drainage is crucial to maximizing its production since most hemp plants failed to grow in poorly drained soils [58].

### 3.2. Day Length

Hemp is a short-day plant hence very sensitive to photoperiod. The day length affects the amount of light received by the hemp plant, and has been reported to strongly influence the productivity in different hemp varieties. The shift from the vegetative to flowering stage in hemp is dependent on day length and variety. However, it has been reported that some varieties initiate flowering regardless of day length, while others require shorter days to transition to flower developmental stage [59]. Data on the specific number of light hours required per day are limited and thus require further exploration.

### 3.3. Plant Spacing

Plant spacing in hemp is dependent on the type of hemp cultivated, i.e., fiber, seed, or CBD. Generally, hemp planted at high density encourages taller height and restricts flowering. Hemp cultivated mainly for fiber are planted closely together in order to promote stalk elongation with reducing branching, attributes that will ensure longer and stronger fiber yield [60]. It also results in the production of high-quality hemp crop because the high-density stands can suppress weeds, thereby eliminating the need for herbicides. On the contrary, hemp planted for seed and CBD are well spaced out to maximize the desired flowering and branching.

Hemp is typically planted using seed drills with row spacing ranging from 7.6 to 17.8 cm, particularly when it is grown for fiber or seed products. However, seeding rate recommendations vary widely with optimum seeding depth ranging from 1.9 to 3.2 cm. These recommendations ensure minimal competition for the space necessary for vegetative growth and root development [60]. Another study reported the distance between hemp cultivated for fiber to range from 20 to 40 cm [55]. Higher plant populations in fiber varieties of hemp ensure faster canopy closure resulting in minimal weed occurrence [61]. In the case of hemp grown for CBD, the highest yield of flowers or buds was obtained at a plant density of 15 plants  $m^{-2}$ . It was suggested that the highest hemp oil production from seed yielding varieties would require similar planting density [3]. One of the studies reported row spacing in CBD hemp to be similar to hemp varieties grown for seed [62]. In another study, the optimal density for seed production varied broadly and was found to be between 30 and 75 plants  $m^{-2}$  [63]. The most significant variation was found in hemp cultivated for fiber production, where a study reported that sowing densities ranged from 50 to 750 plants  $m^{-2}$  [64]. A suitable plant spacing to obtain high yields of the stem, seed, and inflorescence altogether was found to be 120 plant  $m^{-2}$ , with an inter-row spacing of 0.5 m [65]. Another study reported the optimal density for the cultivation of CBD hemp to be 10 plants  $m^{-2}$  [66]. Results from these studies indicate that optimum hemp spacing is a function of the type of hemp variety grown and soil environmental conditions. However, it is clear that information regarding recommended spacing for optimal CBD and seed hemp production in a wide range of soils and climatic conditions is very limited and needs to be addressed.

#### 3.4. Temperature

Temperature plays a distinct and essential role in hemp production throughout different growth stages. Hemp grows under a wide range of environmental conditions, and a lot of studies have reported that it is more adapted to the temperate climatic zone. Although hemp grows best when the mean daily air temperatures are between 16 and 27 °C, it can also tolerate colder and warmer conditions. For example, at low temperatures of 8–10 °C, the seed takes 8–10 days to germinate. Young seedlings with 8–10 leaves can tolerate some exposure to frost typically up to −5 °C. The plant height attained in the field in 90 days can be achieved in 40 days by plants grown at 19 °C in a controlled condition by regulating the growing degree days (GDD). Hemp grown in the Mediterranean requires about 1900–2000 °C GDD for fiber production and about 2700 to 3000 °C GDD for seed production [27]. However, ideal GDD requirements for high yielding CBD hemp need more investigation.

#### 3.5. Rainfall

Hemp requires high moisture throughout its growing season, but most notably during the first six weeks of growth when the young plants are getting established [57]. After they are well rooted, plants can endure drier conditions, but severe drought can negatively hasten up maturity and cause the production of stunted plants. Ideally, hemp requires a rainfall of 63 to 75 cm per annum. Crop water requirement and uptake varies depending on the type of hemp variety, soil, climatic conditions, and management practices. Hemp roots are capable of penetrating the soil up to 2–3 m to extract moisture, provided the soil is not waterlogged and pans do not impede the plant roots. A study conducted in Europe reported that hemp yield strongly depended on the amount of rainfall between June and July, which was found to be as high as 700 mm [60]. Other studies indicate that hemp requires 25–35 cm of moisture during the vegetative stage and 50–70 cm of available moisture for optimum yield.

### 4. Hemp Fertility Requirements

#### 4.1. Effect of Nitrogen

Nitrogen (N) plays a significant role in crop nutrition and yield, hence, is considered the most crucial nutrient in hemp production. This fact is well depicted by studies that have reported the responses of hemp to N fertilization. Application of N fertilizers positively affect hemp plant height,

biomass for fiber hemp varieties, and grain and protein content for seed yielding varieties. The N requirement is high during the first one month of hemp growth so N is usually applied at sowing in most field experiments. A study reported that 79% of total N uptake occurred within the first month with a daily N uptake of 3–4 kg ha<sup>-1</sup> [66]. Another study reported that N application after sowing or applied by split method did not increase stem yield when compared to N distribution at sowing [67]. An increase in 60 kg dry matter (stem biomass) kg<sup>-1</sup> N applied was noticed as N fertilization was increased from 0 to 120 kg N ha<sup>-1</sup>. However, beyond N fertilization rates of 150 kg ha<sup>-1</sup>, no further yield increase was reported [67]. Excess N application stimulates rapid stem elongation which makes the hemp crop more susceptible to lodging [15]. Inadequate N, on the other hand, will cause loss of yield, while excess will reduce the fiber quality. Various experimental results have confirmed that N fertilizer application should be determined based on initial soil fertility. A study conducted by [16] also concluded that hemp growth response to fertilizer N was negligible in soils rich in N. Due to differences in environmental conditions and methodologies, the stem biomass per unit of N fertilization cannot be accurately determined from literature data and therefore warrants more investigation. A recently conducted study reported that N deficiency symptoms were observed in greenhouse-grown hemp for CBD when the N content in the leaf tissue analysis was 1.62% [68]. However, more research is needed to evaluate the effect of N application on the yield of seed and CBD hemp varieties under field conditions.

#### 4.2. Effect of Phosphorus

Phosphorous (P) is an essential macronutrient required throughout hemp growth stages. However, its demand gradually increases as the plant matures. P is also essential during the early growth stages of hemp as it plays a major role in imparting strength and resistance against pests. Limited research has been conducted on the effect of P on hemp production. Even though P application increases plant height, it was concluded that its effects on hemp biomass and seed yields were inconsistent and minimal, therefore very negligible [69]. Previous research also showed that hemp response to P might vary depending on growing conditions [70], and its availability plays an important role in the elasticity and tensile strength of hemp fibers. A study reported that P uptake by hemp ranged from 52 to 67 kg ha<sup>-1</sup>, and P fertilization had no effect on stem yield [67]. P enhancement treatment caused a 16% reduction of THC concentration but did not affect CBD concentration in the flowers [71]. P deficiency can also affect hemp ability to uptake other essential nutrients, and can subsequently reduce the plant health, immunity to disease, crop quality, and yield. Hemp plants suffering from P deficiency show visual symptoms including stunted growth and development of reddish-purple color in the leaf due to anthocyanin pigment formation [72]. In a recent study, leaf tissue analysis of P was reported to be 0.09% for P deficient CBD hemp plants grown under greenhouse conditions [68].

#### 4.3. Effect of Potassium

Hemp is less responsive to potassium (K) compared to N and P fertilization, and very few experiments evaluating the effect of K on hemp have been conducted. One of the studies reported that K did not significantly affect hemp biomass and seed yield [68]. K is a macronutrient and is required in substantial quantities by hemp. K uptake increases as the crop grows which is similar to trends observed for P [73]. However, in the case of fiber hemp varieties, the peak uptake occurs during fiber developmental stages. K has been reported to have a more significant effect on fiber quality than P [27]. K fertilizer trials suggested that hemp should receive 175 kg K ha<sup>-1</sup> [74]. A recent study conducted on CBD hemp under greenhouse conditions reported the K content in leaf tissue to be 0.41% for K deficient hemp plants [68]. However, the effect of K fertilization on the seed and CBD yields in hemp varieties in the field have not been reported to our knowledge.



#### 4.4. Effect of Other Nutrients

Hemp plants need a relatively substantial amount of magnesium (Mg) and are very sensitive to Mg deficiency. Mg-deficient hemp plants are characterized by dark green younger leaves, grayish-white patches in older leaves due to loss of chlorophyll, and slowed root and shoot development. The need for micronutrients for hemp is highly dependent on soil nutrient conditions, organic matter content, and soil texture. Copper (Cu) deficiency is commonly experienced in peat soils and its deficiency in hemp could lead to breaking of stems. Manganese (Mn) and boron (B) deficiencies have also been reported in hemp [75]. A study conducted in Russia on peat-humus soils have shown that the yield and quality of fiber and seed hemp fertilized with sufficient P and K could be increased by supplemental application of 1 kg of B (as boric acid ( $\text{H}_3\text{BO}_3$ )), 1 kg of Cu (as copper sulfate ( $\text{CuSO}_4$ )), and 10 kg of Mn (as manganese sulfate ( $\text{MnSO}_4$ ))  $\text{ha}^{-1}$  [76]. Leaf tissue analysis of CBD hemp during deficiency symptomology for a wide range of nutrients including Mg, Sulfur (S), B, Cu, Mn, molybdenum (Mo), and zinc (Zn) were reported in a study conducted by [68]. This study also suggested that with the exception of N, K, B, and Cu, other nutrient deficiencies did not significantly decrease the CBD hemp yield. More research at field scale is necessary to evaluate the effect of micronutrients on the cannabinoids in CBD and seed yielding hemp varieties.

### 5. Hemp Agronomic Management Practices Intended to Improve Soil Health

#### 5.1. Crop Rotation

Crop rotations are essential to disrupt pest cycles, maintain and enhance soil health, and crop diversification. Crop rotations also increase soil organic carbon and soil organic matter content [77]. Hemp grown for fiber can produce  $25 \text{ t ha}^{-1}$  aboveground biomass and large quantities of root biomass that can be distributed deeper in the soil as compared to corn or wheat [16]. Over two-thirds of organic matter is replenished to the soil when fiber hemp is field retted, and improves soil porosity and friability [78]. Fiber hemp plant is also deep-rooted and has been found to influence the soil structure. Its taproot penetrates deep into the ground aerating the soil at the same time building soil aggregates and preventing erosion [79]. A group of researchers evaluated hemp grown in monoculture and in rotation with wheat [80]. They concluded that hemp could be grown for several years in conventional monoculture without yield declines. Hemp increased wheat yields in two of three growing seasons and the researchers concluded that hemp had great potential as a predecessor for wheat under rainfed Mediterranean conditions. Another study reported a 10%–20% increase in the yield of wheat followed by the cultivation of hemp [55]. More recent research where soybean was grown as monoculture demonstrated that hemp cultivated earlier had a positive effect on soybean growth [81]. Some reports have also suggested that growing hemp following alfalfa can improve hemp yield.

Hemp plant has been reported to decrease the population of nematodes and pathogenic fungi in the soil, and it has been stated that hemp has the potential to be grown without the use of pesticides, herbicides, or fungicides [82]. Three soil pathogens (the fungus *Verticillium dahlia*, root-knot nematodes *Meloidogyne chitwoodi*, and *Meloidogyne hapla*) were suppressed by hemp, and it was concluded that introducing hemp in a crop rotation might enhance soil health [83]. Hemp's high planting density, rapid soil surface coverage ability and fast growth (especially the fiber yielding) varieties after emergence render it very competitive against weeds [61]. This makes it potentially one of the greatest agronomic and environmental benefits of cultivating hemp in rotation with other crops. An experimental study also demonstrated hemp was able to suppress weed effectively without the use of herbicide, except for places where plant densities were relatively low, between 10 and 30 plants per  $\text{m}^2$  [82]. In order to introduce hemp successfully into a crop rotation, information on the optimal sequencing of hemp with other crops, the effect of integrating hemp into rotations on pests, and potential effects of hemp on soil health is necessary and needs to be further investigated across diverse growing conditions in the US.

## 5.2. Organic Amendments

For generations, animal manures and composts have been identified as soil builders because of their enormous impact on improving soil health [84,85]. The nutrient content of animal waste varies depending on different factors like feed source and type, animal age, handling and storing techniques, temperature, and moisture content. Organic amendments are rich with nutrients that are essential for plant's nutritional requirement, like N, which is one of the crucial nutrients required for hemp cultivation. They also add carbon to the soil and improve soil biodiversity. Organic amendments also help reduce nutrient run-offs and leaching of nitrates in the soil. Although various environmental benefits can be derived from manure application, these benefits are optimized when it is applied at an appropriate time and at appropriate amounts and techniques. Improper manure management might contribute to increased greenhouse gas emissions [86]. Organic amendments come in various kinds, and can be used depending on location and availability. The commonly used types of manures in hemp production are horse, cow, and chicken manure. It has been reported that hemp is naturally adapted to using mammalian manure, e.g., horse manure as fertilizer, and it can also efficiently employ stocks of livestock manure [78]. Composting of manure is a process that is recommended because it enhances the quality of manure and has been reported to improve soil health properties [85]. Chicken, horse, and cow manure are recommended to undergo composting before usage to decrease the likelihood of pathogens. It has been reported to contain about 1–2% N and 1–3% K but amounts might vary depending on the type of animal waste used. Although there is a huge potential to incorporate animal wastes for hemp production not much has been reported.

Another source of organic amendment would be the application of mulches in hemp cultivation. Organic mulches, i.e., chopped leaves, straw, grass clippings, compost, wood chips, shredded bark, sawdust, pine needles, etc., application have multiple benefits. Mulches are intended to moderate soil temperature fluctuations, improve soil structure by facilitating water and oxygen entry, provide conducive habitats for beneficial soil organisms, e.g., earthworms, reduce soil-borne pathogens, minimize surface runoff, prevent erosion, and reduce weed seed emergence. In cases where hemp is grown for fiber, most of the leaves are returned to the field hence serving as mulch and thereby preserving soil moisture and increasing microbial biodiversity in the soil [78]. Furthermore, when retting of hemp is done on the field, the stems are left behind, which also serves as soil mulch. Many of the residual nutrients from the stalks are then returned to the soil, making them available for the next year's crop. Most of the studies reported on CBD hemp uses black or white plastic mulches, and not much is reported on the use of organic or biodegradable mulches.

## 5.3. Cover Crops in Hemp Rotation or Using Hemp as a Cover Crop

A cover crop is a crop that is planted mainly to the ecological benefit of soil rather than crop yield [87]. Cover crops are typically grass or legumes and mostly grown in winter before the summer cash crop. Incorporating leguminous cover crops that have biological N fixing capacity also has the potential to provide supplemental N requirements for the main crop in the cropping system. Cover crops also provide ecological benefits to the soil by suppressing weeds and pest pathogens, control soil erosion, help build and improve soil fertility, and increase biodiversity [85,88]. Hemp is an annual crop that could make it a good fit into crop rotation, although very few studies have been conducted on the rotation effects of hemp. In addition, since certain varieties are very photosensitive, there are challenges associated with using hemp as a cover crop. It has been reported that fiber hemp in crop rotation as a cover crop can suppress weed efficiently for the following crop [16] thereby, enhancing soil health by reducing the need for synthetic herbicides. A report suggested that using annual N-fixing cover crops, i.e., sweet clover, fababeans, peas, etc., could supplement the N requirement of hemp later in the season [59]. Some studies also showed that incorporating hemp in a crop rotation has allelopathic effects, thereby reducing pest nematodes. Therefore, hemp can serve as a nematicide for certain crops, e.g., potatoes, maize, peas, etc., that are susceptible to nematode infestation [89]. Certain hemp residues are also well suited for use as botanical insecticides [18].

## 6. Conclusions

Hemp production in the USA has been on the rise since the 21st century and more US states have attempted to establish a hemp production system following deregulation according to the 2018 US Farm Bill. This has significantly increased the potential for hemp markets in America. Many products can be derived from hemp, but the most enterprising situation for hemp in the USA is oilseed production and CBD extraction from hemp flowers for pharmaceutical uses. This review indicates that although there is a renewed interest in the adoption of hemp, its production in the USA remains limited partly because of unclear agronomic guidance and fertilization recommendations, especially for CBD hemp in different soil and environmental conditions. Hence, it is essential to explore and update the scientific knowledge of hemp in order to understand and recommend the best management practices. Hemp cultivation requires intensive management, and environmental conditions like seedbed preparation, soil type, day length, seeding rates, dates, harvest dates, etc., are all impacted by the type of hemp variety employed. Hemp varieties grown for fiber, oil seed, and CBD have different fertilizer requirements and most of the fertility trials in the past have been limited to hemp for fiber. This review also describes the potential of integrating agronomic management practices intended to improve soil health like crop rotation, cover cropping, mulching, and manure application to hemp cultivation. Hemp is a potential emerging multipurpose crop with not only economic but also soil health benefits through phytoremediation, bio-sequestration, and bioenergy production. More research on optimal agronomic production techniques needs to be conducted for increased productivity and sustainability in order to achieve the full potential of this high promising multi-purpose crop.

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