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Climate smart hemp seed solutions

R.S. Raghuvanshi* and Apurva

Department of Food Science and Nutrition, G. B. Pant University of Agriculture and Technology, Udham Singh Nagar- 263 145, India

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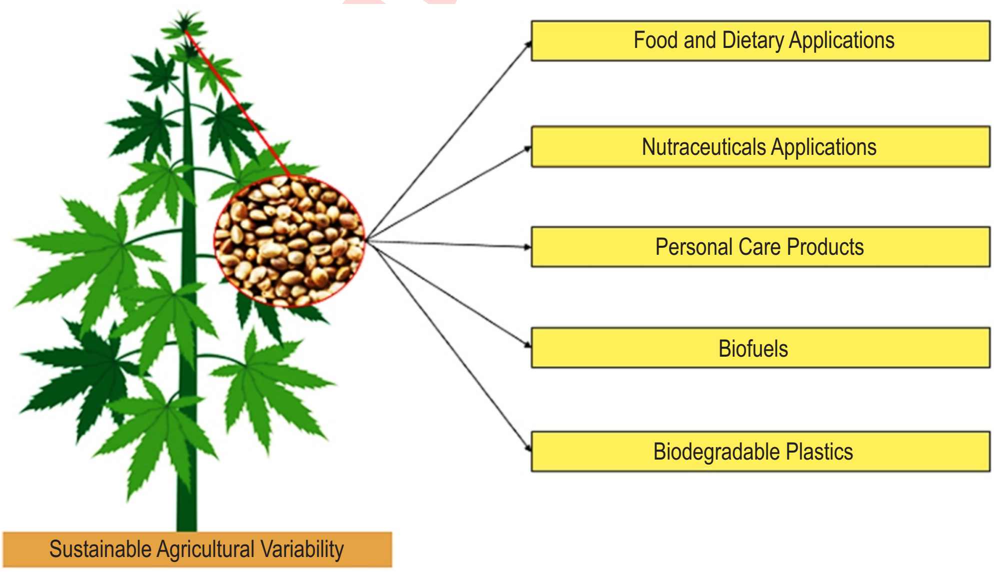
***Corresponding Author Email:** rsr7815@gmail.com ***ORCiD:** https://orcid.org/0000-0002-8368-653

Abstract

This review focus on hempseed (*Cannabis sativa* L.) as an emerging climate-smart crop with relevance to sustainable agriculture, environmental protection, and nutritional security. Recent evidence suggests that hemp performs efficiently across a wide range of agro-climatic conditions, requires relatively modest external inputs, and contributes meaningfully to carbon sequestration, with reports indicating that a single hectare of cultivation can absorb up to 22 tons of carbon dioxide annually. In addition to its agronomic advantages, hempseed possess a dense nutritional profile, supplying easily digestible proteins, essential fatty acids, dietary fiber, and several bioactive constituents of health relevance.

Beyond its role in human nutrition, hempseed and associated plant fractions support diverse industrial applications, including the development of biofuels, biodegradable materials, nutraceutical formulations, cosmetic products, and functional foods. These uses provide sustainable alternatives to conventional raw materials that are often associated with high environmental costs. Evidence from applied case studies further demonstrates the successful incorporation of hemp into crop rotation systems, as well as its adaptability across multiple industrial value chains. Collectively, these characteristics highlight hempseed as a multifunctional agricultural resource with the capacity to lower environmental pressures, enhance soil and ecosystem functioning, and contribute to more resilient food systems. Strategic expansion of hemp cultivation, supported by targeted research, enabling policy environments, and innovation-driven value addition, may strengthen its contribution to circular economy frameworks and climate adaptation strategies.

Key words: Carbon sequestration, Climate change, Hempseed, Nutraceuticals, Sustainability



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Introduction

Climate Change Crisis: Climate change is emerging as one of the most critical challenges of this century, with wide-ranging consequences for ecosystems, agriculture, and human health. Its effects include extreme weather changes, biodiversity loss as well as soil and water degradation. India is among the countries that are most affected, facing recurrent floods, droughts, and heat waves that threaten both livelihoods and food security (Hussain *et al.,* 2024). Agriculture is central to this issue because it contributes significantly to greenhouse gas emissions, yet it also offers substantial opportunities for mitigation through climate-smart practices. Historically, food systems relied on diverse plant-based resources that ensured both nutritional adequacy and ecological balance. Modernization, globalization of diets, and the decline of indigenous food practices have reduced dietary diversity and weakened food system resilience (Dhyani and Raghuvanshi, 2023). To counter this,emphasisshould be given for cultivating multipurpose crops that combine nutritional value with ecological adaptability and industrial potential.

In the past, climatic variations have been largely shaped by natural forces. Today, however, human-driven activities such as fossil fuel use, large-scale agriculture, and deforestation are the primary contributors to global warming (IPCC, 2019). These processes not only accelerate greenhouse gas emissions but also strain ecosystems worldwide. Within this context, both in India and globally, sustainable land-use management and diversification of food systems are increasingly recognized as essential strategies for lowering emissions while supporting adaptation (Sonwani *et al.,* 2021; Krishnan *et al.,* 2020). Hemp (*Cannabis sativa* L.) has re-emerged as a promising option in these discussions. The crop is highly adaptable to varied agro-climatic conditions and can grow with minimal chemical inputs. Importantly, hemp is regarded as a near-zero-waste crop because every part of the plant including seeds, stalks, flowers, and leaves holds commercial value. Nutritionally, hemp seeds are rich in protein, unsaturated fatty acids, dietary fiber, and essential minerals, making them suitable for both food and health applications (Farinon *et al.,* 2020; Kamle *et al.,* 2024).

On the industrial side, hemp offers raw material for textiles, bio-based composites, fuels, and biodegradable packaging, aligning it with the shift towards circular and sustainable economy (Salentijn *et al.,* 2015; Martinez *et al.,* 2023). Environmental studies further highlights the relevance of hemp as a climate-smart crop. One hectare of hemp has the potential to absorb more than 20 tons of carbon dioxide per year, in many cases sequestering more carbon than conventional crops (Adesina *et al.,* 2020; Biswakarma *et al.,* 2023). Contemporary researches have reported that cultivating hemp outdoors can achieve near carbon neutrality and in some cases, it results in net negative emissions when crop residues are incorporated back into the soil (Meffo Kemda *et al.,* 2024). In contrast, indoor hemp production is considerably more resource-intensive and results inhigher carbon footprints. This comparison highlights the necessity of adopting sustainable agronomic practices to maximise the crop's environmental benefits. Additionally hemp provides ecological services that extend beyond carbon capture. The cultivation of hemp improves the soil structure, suppresses weed growth, enhances pollinator activity, and contributes to the remediation of polluted soils (Citterio *et al.,* 2005; Dowling *et al.,* 2021).

Based on this, it can be observed that hempseed emerges as a climate-smart agricultural option capable of addressing multiple sustainability challenges simultaneously. It contributes to environmental revitalization, broadens dietary alternatives while supporting the development of greener industries. Fusing the findings from agronomy, nutrition research, and life cycle assessments, hempseed can be considered a crop which, builds food system more resilient along with broadening practices to achieve global sustainability objectives.

Hempseeds: Multiple agricultural crops have already substantiated their role in enhancing agricultural resilience with climate smart ecosystems, offering valuable lessons for positioning hemp seed within similar scenarios. A great practical example can be seen in case of millets. Millets were considered marginal after the green revolution era but they have regained significance due to their multifaceted distinctions including tolerance to drought, heat stress with low input requirements. By reintroducing traditional millet cultivation as a part of Odisha Millet Mission has raised yields as well as diversified local diets and strengthened nutritional security. Together with the dietary benefits, the initiative reduced reliance on water-intensive crops and contributed to lower greenhouse gas emissions. Such outcomes show how crop diversification reinforcesnutritional security while also increases the possibilities to mitigate climate change crisis. (Samtani *et al.,* 2024).

National policy in India has also started emphasizing climate-smart resilience through development of different seeds. One of the initiative is the recent release of 109 climate-resilient crop varieties of cereals, pulses, oilseeds, and fiber crops designed to combine enhanced productivity with nutritional benefits by bio-fortification. These innovations highlight the critical role of improved seeds for securing farm incomes and reducing the ecological footprint of agricultural practices (PIB, 2024). Beyond millets, studies on the Indian rice–wheat system reveal the potential of adopting alternative seed crops and agronomic practices. Modeling work using a Social Accounting Matrix framework has shown that shifting even a fraction of land away from rice and wheat to maize, sorghum, and millets could significantly reduce blue water footprints and greenhouse gas emissions, while still maintaining or even improving household incomes. Similarly, practices such as Conservation Agriculture, the System of Rice and Wheat Intensification, and Zero Budget Natural Farming further illustrates the systemic benefits of climate-smart cropping choices (Ajatasatru *et al.,* 2024). Together, these case studies demonstrate that climate sustainability is achievable through seed-focused interventions.

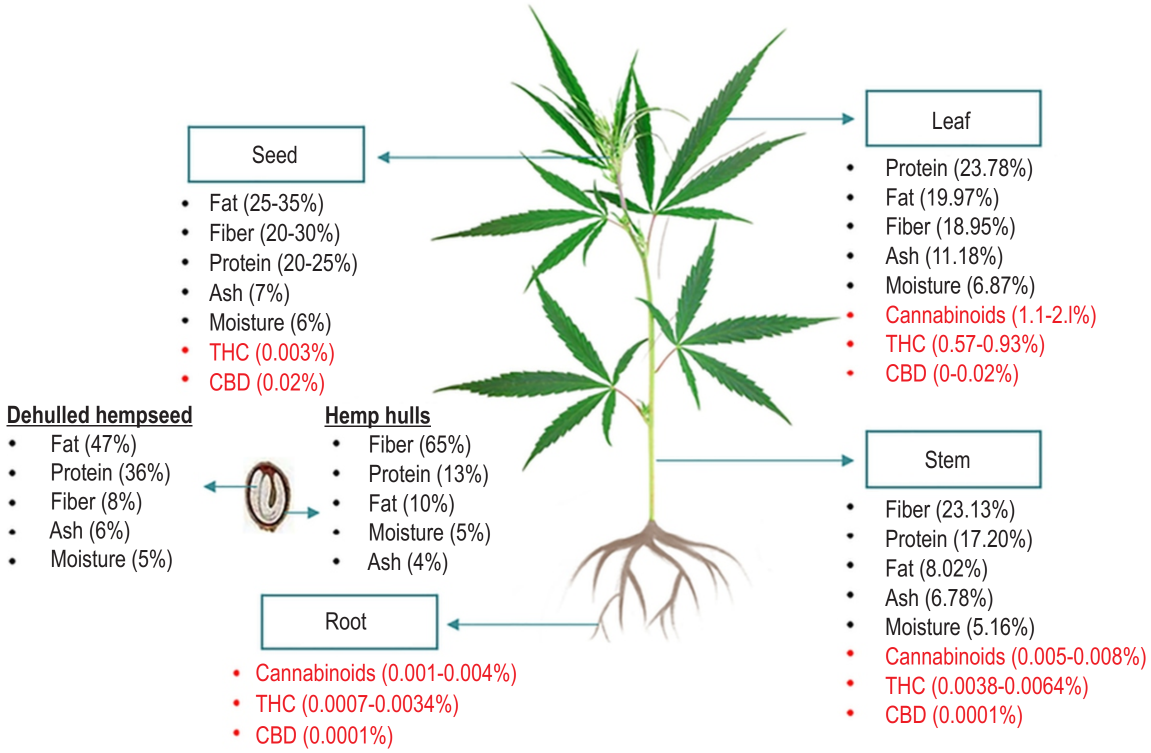

Fig. 1: Nutritional and Phytochemical composition of different parts of the hemp plant (Xu *et al.*, 2022).

They reinforce the idea that hemp can be positioned alongside other proven resilient crops yet with added advantages of multipurpose utility, high carbon sequestration, and industrial applications that extend beyond food security alone. Hemp, botanically known as *Cannabis Sativa* L., belongs to the family Cannabaceae. The term Cannabis implies its cane-like morphology, while sativa indicates that the plant is propagated by seeds rather than vegetative parts. Hemp has been used for a very long time, traditionally as an ingredient for producing ropes, sails, textiles, and paper. Its adaptability to several climatic zones starting from temperate spreading to the tropical regions enabling its household and commercial application for varied uses. (Farag *et al.,* 2017). Archaeological evidences suggest that hemp has been utilized for over 12,000 years, fulfilling its multitudinous roles as food, medicine, and fiber (Turner *et al.,* 1980). Currently, it is cultivated across many regions of the world, namely Europe, Central Asia, the Philippines, and China (Chen *et al.,* 2023). Hemp seeds are about 2.5–3.5 mm in size have a characteristic brown coat patterned by darker striations, are nutritionally rich and have been consumed in various traditional forms such as raw, roasted, and cooked. Recently, hemp seeds are being used rapidly into modern dietary innovations along with medical applications, underscoring their ongoing salience (Farinon *et al.,* 2020). While both hemp and marijuana come from the species (*Cannabis sativa*), they differ drastically at genetic and chemical levels. The most critical distinction lies in their cannabinoid composition. Hemp typically contains not more than 0.3% tetrahydrocannabinol (THC), while marijuana strains may reach THC levels as high as 20% (Adesina *et al.,* 2020).THC is the psychoactive component responsible for the intoxicating effects, while cannabidiol (CBD), another prominent compound, is non-intoxicating and valued for its therapeutic benefits. Cannabis also contains over 120 terpenoids, 125 cannabinoids, numerous phenolics, flavonoids, sterols, and alkaloids (Odieka *et al.,* 2020). The terpenoids largely contribute to the characteristic aroma of the plant. Industrial hemp is selectively bred to contain minimal THC levels and is cultivated specifically for uses that do not involve intoxication. Such fiber-type variants of cannabis are abundant in CBD and are preferred for agricultural, industrial, and nutritional applications (Martinez *et al.,* 2023). The legal and functional differentiation between hemp and marijuana is based primarily on THC concentration, which determines whether a given variety is suitable for industrial or medicinal use. Hempseed's nutritional and compositional diversity, along with its low THC content, makes it a safe and sustainable ingredient for food systems and industrial applications. Its increasing global relevance stems from its potential to contribute simultaneously to nutrition, health, and environmental sustainability.

Sustainable Agricultural Viability: Hemp cultivation demonstrates remarkable adaptability across climatic zones, performing well in temperate, tropical, and subtropical regions.

Optimal conditions include moderate temperatures, adequate humidity, and an annual rainfall of approximately 600–700 mm (Adesina *et al.,* 2020). In India, the wide range of agro-climatic zones—from the Himalayan states of Uttarakhand, Himachal Pradesh, and Jammu & Kashmir to the northeastern region, Uttar Pradesh, and Madhya Pradesh—provide highly favorable conditions for hemp cultivation. Its adaptability, combined with comparatively low input requirements, makes hemp a versatile crop, well-suited for both smallholder subsistence farming and modern, commercially driven agricultural systems.

Cultivation of hem as a rotational or cover crop, significantly improves the soil health. Whereas on decomposition it helps in enhancing the soil structure and also the microbial diversity thereby inhancing the bioavailability of nutrients. As a thermophilic crop, it can with stand higher temperatures thus it can adapt well with the stresses associated with climate change (Berenji *et al.,* 2001). The crop can be grown with conventional crops like cereals and legumes in rotation cycles, either as fiber or oilseed crop (Kostuik *et al.,* 2019). Another great merit of hemp is the comparatively low demand in terms of resources of irrigation, fertilizers, and pesticides. Its natural resilienceto several common pests and pathogens makes it suitable for stable yields without relying on chemical inputs (Buckley, 2010). Studies have concluded that hemp also possess and ability to suppress growth of soil-borne pathogens such as *Verticillium dahliae* as well as the root-knot nematodes (*Meloidogyne chitwoodi* and *M. hapla*), thus not only promoting healthier soils but also decreases the need of synthetic pesticides in agricultural set up (Kok *et al.,* 1994).

In the context of climate change mitigation, hemp has drawn higher attention for its ability as efficient carbon sink. The rapid growth and ability to produce large amounts of biomass allow it to capture a considerableatmospheric carbon. Estimates indicates that even a single hectare of hemp can absorb roughly 22 tons of CO_2 each year, this not only surpasses many staple crops in this context but also equalling or exceeding that of certain forest ecosystems (Adesina *et al.,* 2020; Biswakarma *et al.,* 2023). Beyond the carbon sequestration characteristic, hemp also contributes long-term soil regeneration. Its characteristic taproot system boosts exchange of gases and increases infiltration of water which inhances the formation of stable soil aggregates, resulting in better soil health and less erosion. In addition, the crop residues can be further converted into biochar, a soil amendment for boosting soil fertility and locking free carbon within the soil for an extended period of time. Both these ecological and agronomic benefits together positions hemp as a climate-smart crop with the capability to strengthen agro ecological resilience with environmental restoration.

Climate Smart Solutions of Hempseed: Hempseed derived from *Cannabis sativa,* is increasingly drawing attention as an important component of the climate-smart agricultural systems because of its sustainable cultivation practices and a wide range of operations across industries. From a nutritional point of view, hempseed is particularly significant with high-quality plant protein, favorable ratio of essential fatty acidsas well as diverse micronutrients important for human health. It provides a suitable alternative to animal-based proteins, thereby contributing to climate-friendly dietary transitions and lowering the ecological pressures linked to livestock production when incorporated in diets. Along with nutrition, hempseed also plays an important role in sustainable industrial development. Derivatives of hempseed such as oilcakes etc., have been utilized for producing different grades of biofuels, biodegradable packaging, cosmetics as well as a wide range of eco-friendly products. It can replace petroleum based raw materials which can reduce environmental footprint of industrial processes while supporting circular economic models that are less waste-intensive.

Food and Dietary Applications: Hempseed is receiving increasing attention in the global food sector because of its health-promoting qualities and wide-ranging applications. Nutritionally, it constitutes approximately 20–30% carbohydrates, much of which occurs as insoluble fiber, 25–35% lipids that are especially rich in polyunsaturated fatty acids, and 20–25% proteins that are highly digestible (Vonapartis *et al.,* 2015). Evidence from both *in vitro* and *in vivo* studies have highlighted the functional benefits of hempseed, reinforcing its value as a promising ingredient for the development of health-oriented foods. Compositional profiling has reported protein content of 20.4% with a digestibility rate of 66.69%, lipid levels of 28.7%, and carbohydrate content of 16.87%, providing an estimated energy value of 385.72 kcal per 100 g. Hemp seeds are also a notable source of dietary fiber, contributing 26.83 g per 100 g (primarily insoluble), and exhibit strong antioxidant potential with 221.31 mg GAE per 100 g and 68.27% DPPH radical inhibition capacity (Singh *et al.,* 2021). Concern about the food system emissions have further highlighted the value of plant-based proteins such as hemp. Livestock farming, particularly meat and dairy production, has been identified as a leading contributor to agricultural greenhouse gases in India, with ruminant production showing extremely high impacts for instance, mutton yields over 45 kg CO_2-equivalents per kilogram of product (Vetter *et al.,* 2017). In contrast, hempseed provides a protein-rich alternative that rivals or surpasses other oilseeds like sunflower and canola in protein content (Potin and Saurel, 2020). The proteins, primarily edestin and albumin, are digestible, contain all the essential amino acids, and have a biological value comparable to egg protein, supporting its role as a reliable source of plant-based protein (Mikulec *et al.,* 2019).

Hempseeds are used to formulate different products including flour, oil, and protein concentrates, these products can be further applied in plant-based foods for health-focused consumers. Plant–based dairy alternatives, meat analogues, and fortified baked goods are some the applications of hempseed in this regard. The mild, nutty flavour of the hempseed complemented by the aromatic terpenoids, adds favourable sensory qualities for better palatability and consumer acceptance (Shen *et al.,* 2021). Ertaş and Aslan (2020) suggested that incorporating up to 20% of hemp flour inwheat flour can enhance protein and fat while lowering the carbohydrate content and boosting the antioxidant activity, with raw hemp flour contributing most positively to overall acceptance.

In addition to the development of traditional baked products, hemp-derived ingredients have also added significantly to gluten-free product technologies. Substitution or incorporation of hemp flour and protein into gluten-free bread formulations raise the fiber and protein levels along with improving the loaf volume, crumb texture and shelf life (Korus *et al.,* 2017). In beverages, hempseed fermentation with probiotic strains not only maintain the microbial viability but also stimulates short-chain fatty acid production which is highly beneficial for gut health (Nissen *et al.,* 2020). Such benefits are also observed in cereal based product formulations. Enrichment of bread dough with 20% hemp flour enhance the protein content from 11.73 to 16.15 g per 100 g and decreases the starch levels (Pojić *et al.,* 2015). Technological advances including high-pressure homogenization and pH-shift methods have improved the stability and texture of hemp-based milk alternatives, enabling clean-label solutions without relying on chemical stabilizers (Wang *et al.,* 2018).

Studies on rice-based extrusions fortified with hempseed powder have shown a remarkable increase in the antioxidant activity, phenolic content and textural properties, especially when whole hemp seed powder is used (Norajit *et al.,* 2011). Similar benefits have been reported with composite flours that combine hempseed with chickpea and corn silk, which demonstrates the enhanced nutritional quality, greater dietary fiber, and higher antioxidant activity compared with traditional wheat-based flours (Raghuvanshi *et al.,* 2024). Hemp protein is also gaining attention in the field of alternative proteins, particularly for use in developing meat analogues. Research by Zahari *et al.* (2020) demonstrated that substituting up to 60% of soy protein isolate with hemp protein in high-moisture extrudates resulted in meat substitutes that were nutritionally superior while maintaining comparable texture and sensory acceptability. Although slight differences in hydration and color were observed, these did not compromise the overall quality of the product.

Hemp seed also has a good position when it comes to sustainable food packaging solutions. Protein isolates obtained from hemp have been successfully used to form edible films and coatings with desirable physical strength, barrier qualities, and biodegradability (Yin *et al.,* 2007; Suhag *et al.,* 2020). These edible films can reduce reliance on plastics while extending the shelf life of foods. Hempseed offers a dual advantage: it is nutrient-dense, serving as an excellent source of plant proteins, fibers, fatty acids, and antioxidants, and it functions as a raw material for sustainable industrial products.

Nutraceutical and Therapeutic Applications: Hemp seeds are increasingly gaining recognition within the nutraceutical sector owing to their dense nutritional composition and bioactive constituents with clinically relevant health-promoting properties. Rich in essential amino acids, polyunsaturated fatty acids, dietary fiber, vitamins, and minerals, these seeds are regarded as beneficial in the management of several metabolic and degenerative disorders (Kamle *et al.,* 2024). Recent biofunctional studies have highlighted the therapeutic potential of hempseed-derived proteins and peptides. These biomolecules exhibit activities such as antihypertensive, antidiabetic, and anti-inflammatory effects, all of which have implications in the prevention and management of chronic diseases (Aguchem *et al.,* 2022; Chen *et al.,* 2023). The proteins present in hempseeds are characterized by high digestibility, low allergenicity, and favorable techno-functional traits, making them suitable for both conventional food applications and specialized formulations aimed at combating malnutrition or supporting targeted dietary interventions.

Therapeutic applications of hemp have long been acknowledged by several traditional medicine systems. In Chinese folk medicine, hempseed oil has been used to relieve symptoms of rheumatoid arthritis and to improve circulation (Cho *et al.,* 2005). Likewise, Ayurvedic literatures also describe a cannabis-based preparations for addressing various health and lifestyle problems such as sleep disturbances, aches and reproductive health concerns (Malabadi *et al.,* 2023). Within the Ayurveda, hemp is associated with calming properties of the *Vata* dosha governing movement and nervous system. By bringing balance to this dosha, hemp can be used to ease anxiety, restlessness, and insomnia, thereby helping to restore mental stability (Gupta, 2023). Various clinical assessments have highlighted the cardiovascular benefits of hempseed oil. A four weeks clinical trial of daily supplementation with 30 ml of oil provided better results in lipid metabolism by reducing the total cholesterol, low-density lipoproteins along with triglycerides, while raising the levels of protective high-density lipoproteins (Schwab *et al.,* 2006). Such findings suggest that hempseed oil could be used as a valuable dietary intervention for cardiovascular health promotion (Kaushal *et al.,* 2020).

Hemp-derived phytochemicals are also connected to anticancer mechanisms. Cannabidiol, especially has shown particular promise as it interferes with tumor progression and stimulates apoptosis in malignant cells. Experimental studies have reported that CBD exposure can reduce the proliferation of prostate cancer cells and suppress the secretion of prostate-specific antigen (Sarfaraz *et al.,* 2005). Similar effects have also been observed in gliomas and other cancer types, pointing to the potential of hemp-based compounds as supportive tools in oncology (Rupasinghe *et al.,* 2020). Hempseed oil further demonstrates antimicrobial potential. Ali *et al.* (2012) reported that the oil inhibited a broad spectrum of bacterial strains with efficacy similar to antibiotics such as Gentamicin and Benzyl penicillin. Its activity against both Gram-positive and Gram-negative bacteria highlights its potential for use in natural antimicrobial formulations. Regarding metabolic disorders, bioactive peptides from enzymatic hydrolysis of hempseed proteins have demonstrated a good antihypertensive properties. Malomo *et al.* (2015) reported that these peptides hydrolysates led to significant reduction in systolic blood pressure in spontaneously hypertensive rats. Interestingly, alcalasehydrolyzed hempseed proteins provided strongest immediate effect on blood pressure, while pepsin-derived hydrolysates delivered longer-lasting benefits.

Polyphenols present in hemp add further value to its nutraceutical potential. While they serve to protect the plant from environmental stress, in humans they function as antioxidants and regulators of cellular metabolism. Regular intake of these compounds may help lower the risk of chronic conditions such as cardiovascular disease, diabetes, obesity, and cancer by reducing oxidative stress and controlling inflammation (Singh *et al.,* 2021). The rich nutritional and biofunctional profile of hemp has also made it an appealing ingredient in sports nutrition. Hempseed has a complete amino acid composition with great digestibility providing support for muscle protein synthesis and post-exercise recovery. Alongside, the presence of dietary fiber, anti-inflammatory compounds, and antioxidants contributes to better digestion, reduced oxidative stress, lower muscle soreness as well as improved endurance (Chen *et al.,* 2023; Pareek *et al.,* 2021; Kamle *et al.,* 2024). For athletes and fitness enthusiasts, adding hempseed protein or oil to the diet is increasingly seen as a natural way to boost recovery and performance without relying solely on conventional supplements.

Personal Care: Hempseed and its derivatives can be studied as eco-friendly alternatives for the personal care industry. Usage of hempseed oil into several cosmetic formulations decrease the dependence on petroleum-based inputs that leads to pollution and waste generation. Hempseed oil with its remarkable lipid profile is rich in essential fatty acids and other bioactive compounds making it a suitable product for various dermatological formulations. Research has shown that it supports skin hydration, eases irritation, and offers natural anti-aging benefits. Its incorporation into sunscreens and skin-repair formulations has also been documented, with evidence pointing to soothing and regenerative effects that strengthen the skin's barrier function (Leyva-Gutierrez *et al.,* 2020). Another notable bioactive compound derived from hemp is Cannabidiol which also has attracted growing interest in dermatological researches. While application, the interaction of Cannabidiol with cutaneous receptors influences the key mechanisms such as keratinocyte proliferation, immune responses and inflammation. This offers therapeutic applications for improving skin conditions like eczema, psoriasis, and contact dermatitis. Topical applications that target the endoannabinoid systems may, thus, offer a non-invasive and plant-based approach for managing hyper proliferative and inflammatory skin diseases (Madras, 2015). Hempseed oil has been used in traditional healing systems for curing dryness, irritation, and inflammatory skin conditions. Modern researches also confirm this, hempseed has emollient properties which helps in restoring the skin's barrier and reducing the trans-epidermal water loss (Callaway *et al.,* 2005). Incorporation of hemp oil into contemporary cosmetic formulations, hemp oil also improves the adherence to skin cells which not only increases the performance, but also the consumer acceptability (Rupasinghe *et al.,* 2020).

Biofuel from Hempseed: A transition can be seen towards opting renewable sources of energy and green fuels has resulted in studying and finding alternatives of fossil fuels. Biodiesel, which consists of long-chain fatty acid esters produced via transesterification of oils or fats with alcohol in the presence of a catalyst, has emerged as a promising solution. Compared to conventional diesel, biodiesel can lower the net carbon dioxide emissions by as much as 78 percent over its life cycle, contributing significantly to climate change mitigation efforts (Sharma and Singh, 2009).

One of the notable advantages of biodiesel is that it can be utilized in standard diesel engines without requiring mechanical modifications. The choice of feedstock, however, is crucial in determining the sustainability of biodiesel production. In various parts of the world, feedstocks vary including soybean oil which is predominant in the United States whereas palm oil in South-east Asia and rapeseed oil in Europe (Rosillo-Calle *et al.,* 2009). In India, a substantial share of biodiesel is currently derived from imported palm stearin oil. However, the expansion of oil palm cultivation has been associated with significant ecological harm, including deforestation and peatland destruction. These practices contribute to carbon emissions that cannot be balanced by the carbon absorption potential of the resulting biofuel, especially in the short to medium term (Searchinger *et al.,* 2018).

Hempseed oil presents a more sustainable and environmentally responsible alternative. Its cultivation does not necessitate large-scale deforestation and can be integrated into existing agricultural systems. Moreover, hempseed oil yields are competitive with those of other oil crops such as soybean (Raghuvanshi and Bisht, 2010). The residual biomass of hemp, particularly its stalks, can be repurposed for ethanol production or processed into industrial fiber. These applications not only improve the crop's economic value but also enhance overall resource efficiency by ensuring that multiple parts of the plant are productively utilized. The suitability of hempseed oil as a raw material for biodiesel production through the trans esterification process is also investigated. The resultant biodiesel from hempseed has been compliant to the key international quality standards including ASTM D6751 and EN 14214. It performs well on parameters of viscosity, cetane number, and flash point although it exhibits a limitation in oxidation stability. This issue can be effectively addressed by addition of natural or synthetic antioxidants leading to increased shelf life while preserving the performance (Rehman *et al.,* 2013).

Biodegradable Plastic: The mounting challenge of plastic pollution has intensified the search for biodegradable alternatives that place less strain on the environment. Traditional plastics made from petrochemicals can remain in ecosystems for centuries, contaminating soil and water while breaking down into microplastics that eventually enter the food chain. Biodegradable plastics are designed to decompose into natural elements such as water, carbon dioxide, and biomass through microbial activity, providing a more sustainable solution to plastic waste (Rahman and Bhoi, 2021). Hempseed-derived materials have emerged as viable candidates for the development of biodegradable plastics. Protein concentrates obtained from hempseed oilcake can be used to fabricate biodegradable films with favorable mechanical and barrier properties. Mirpoor *et al.* (2021) investigated the role of protein concentration, glycerol content, and pH levels in film formulation and found optimal results when films were produced at pH 12 using 50 percent glycerol relative to protein weight as a plasticizer. To further improve the structural integrity of these films, microbial transglutaminase (mTGase) was applied to induce protein crosslinking. The resulting films exhibited enhanced tensile strength, heat-sealability, gas permeability, and hydrophobicity, positioning them as suitable alternatives to petroleum-based packaging. Unlike traditional plastics that require complex recycling systems or persist in landfills, hemp-based plastics are fully biodegradable and recyclable. Their life cycle supports a sustainable loop: the plant is grown, harvested, processed into bioplastic, and then decomposed back into the soil to enrich future crops. This circular model minimizes waste and promotes regenerative resource use (Modi *et al.,* 2018).

Hemp plastics are not only environmentally sustainable but also structurally robust. They are reported to be five times stiffer and 2.5 times stronger than polypropylene, a widely used synthetic polymer. Additionally, hemp-based materials cause less wear on industrial machinery due to their composition, making them attractive for large-scale manufacturing (Modi *et al.,* 2018). Their strength, flexibility, and lightweight nature make them ideal for applications in automotive, packaging, construction, and even aerospace industries, where reducing material weight can enhance energy efficiency. Given its biodegradability, mechanical performance, and low environmental footprint, hemp-based plastic offers a compelling alternative to conventional polymers. As industries and consumers shift toward eco-conscious products, the adoption of hemp bioplastics represents a strategic move toward environmental sustainability and innovation in material science.

The importance of hempseed goes far beyond food. It serves as a renewable feedstock for biofuels, contributes to the creation of biodegradable plastics and packaging, and provides natural ingredients for skincare and personal care products. These applications illustrate how hempseed supports circular economic models and reduces dependence on polluting, non-renewable resources. In the context of climate change and shrinking natural resources, hempseed offers a realistic pathway toward sustainable development. It's potential to restore ecological balance, support renewable resource use, and improve human well-being positions it not just as a useful crop, but as a strategic resource for building resilient and sustainable societies.

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