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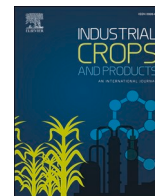
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Short communication

Industrial applications of *Cannabis sativa* (L.): Exploring its biological and nanotechnological potential



Karol Górski^{a,1}, Tomasz Kowalczyk^{b,*}, Aleksandra Gładys^b, Magdalena Glica^b,
Martyna Muskała^c, Laurent Picot^d, Mattia Mori^e, Sophia Hatziantoniou^f,
Przemysław Sitarek^g

^a Institute of Chemistry, Faculty of Science and Technology, Jan Długosz University in Częstochowa, Częstochowa 42-200, Poland

^b Department of Molecular Biotechnology and Genetics, University of Lodz, Banacha 12/16, Lodz 90-237, Poland

^c Research Study Group, Department of Medical Biology, Medical University of Lodz, Muszyńskiego 1, Lodz 90-151, Poland

^d Littoral Environnement et Sociétés UMRi CNRS 7266 LIENSs, La Rochelle Université, La Rochelle 17042, France

^e Department of Biotechnology, Chemistry and Pharmacy, University of Siena, Siena 53100, Italy

^f Laboratory of Pharmaceutical Technology, Department of Pharmacy, School of Health Sciences, University of Patras, Patras 26504, Greece

^g Department of Medical Biology, Medical University of Lodz, Muszyńskiego 1, Lodz 90-151, Poland

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ABSTRACT

The growing demand for modern, smart nano-biosensors and sustainable therapeutic technologies has greatly accelerated interest in plant materials, with *Cannabis sativa* (L.) emerging as a promising resource. The plant has accompanied mankind for thousands of years as a source of fibre and cellulose, as well as various compounds used in industry and medicine. Known for its rich profile of secondary metabolites, as well as its cellulose-rich biomass, *Cannabis sativa* offers great potential for the development of environmentally-friendly nanotechnologies. Such plant-derived nanomaterials are inexpensive, naturally abundant and highly biocompatible, making them suitable for *inter alia* early disease detection, food safety monitoring and pathogen diagnostics. Their use in nanobiotechnology illustrates the versatility of hemp as a raw material for industrial innovation, supporting the transition towards smart and sustainable technologies. This review explores the integration of hemp-derived nanostructures, such as nanoparticles, nanofibres and nanoemulsions, into smart biosensory systems and therapeutic applications; it focuses on the use of cellulose and secondary metabolites for the production of nano-biosensors and therapeutic carriers, and highlights recent advances in the green synthesis of nanostructures from *C. sativa*. By bridging the gap between botanical resources and advanced nanobiosensory and therapeutic strategies, this review highlights the key role of *C. sativa* in addressing global challenges in health, agriculture and environmental sustainability.

1. Introduction

Cannabis sativa (L.), of the *Cannabaceae* Endl. family, is one of the earliest fiber plants cultivated by early sedentary human communities, with its use dating back over 10,000 years (Russo et al., 2008). It is believed to have originated from the southeastern and central parts of Asia (Jiang et al., 2006; Stevens et al., 2016); however, its taxonomy remains a subject of significant debate and has yet to be definitively resolved (Bonini et al., 2018). This plant is an annual, characterized by erect stems which can grow up to five meters tall; it presents palmate

leaves with trichomes, i.e. fine glandular structures containing secondary metabolites. Each leaf comprises five or seven leaflets, featuring sharply serrated edges and a linear-lanceolate shape tapering at the ends. The utility of the plant stems from its wealth of secondary metabolites, which serve as defensive and insect-repellent compounds. To date, 560 compounds have been identified in *C. sativa* (ElSohly et al., 2017; Flores-Sanchez and Verpoorte, 2008). The most significant groups include phytocannabinoids and terpenoids, whose presence and quantity depend on the variety and conditions. Phytocannabinoids are lipid-based compounds, such as alkylresorcinol and monoterpene

* Corresponding author.

E-mail address: Tomasz.kowalczyk@biol.uni.lodz.pl (T. Kowalczyk).

¹ These authors contributed equally to this work

Table 1
Production and characterization of nanofibers and nanocellulose technologies from *Cannabis sativa* (L.).

Type of nanotechnology	Source	Method of obtaining	Characterisation/methods	Ref
Nanofiber	Hemp fibers and shives	Poly(vinyl alcohol) electrospinning, steam explosion treatment, milling, ultrasonication	- reduction in fiber diameter - greater stretching of fibers (jet whipping process)	Sutka et al., (2013)
Microfibers	Hemp stems and branches	Acid hydrolysis coupled with ultrasonic homogenization	- width → 6.91 μm - crystallinity → 40 %–75 % - crystallinity degree → 82 %	Mhlongo et al., (2022)
Cellulose nanofibers	Straw of hemp	Thermo-mechanical and mechanical pretreatment Enzymatic treatment with cellulolytic complex from <i>Aspergillus niger</i> and mechanical treatment	Enzymatic treatment (1000 U/g dry pulp): diameter 25 – 50 nm, length/diameter ratio 10–45, polymerization degree reduced by ~ 58 % Two-step enzymatic – mechanical treatment 1. 50U/g dry pulp: diameter 60 – 100 nm, length/diameter ratio 50 – 70, polymerization degree reduced by ~ 24 % 2. 200 U/g/ dry pulp: diameter 25–100 nm, length/diameter ratio 15–45, polymerization degree reduced by ~ 40 % Increase in α-cellulose content Increase in Kappa content	Kazimierczak et al., (2012)
Cellulose nanofibrils	Hemp hurd fibers	Pulverizing autohydrolyzed hemp hurds	- decreased crystallinity: 50 % → 29 % - increased distribution of charge: 4.5 → 13 (× 10–5 μ eq Vol./L of p-DADMAC)	Agate et al., (2020)
Nanofibres nano fibre films	Hemp fibers	Combined chemical and mechanical (commercial grinder) process	- diameter distribution: 20–100 nm (80 % fibrils: 20–60 nm) - improved tensile strength	Panthapulakkal and Sain (2013)
Nanofibres	Hemp fibres	Combined chemical and mechanical (high pressure steam defibrillation) process	Crystallinity increased by average 2.5 % (compared to untreated fibers) Increase cellulose content: 87 % (up from 74 % in untreated fibers) Crystallinity increased by average 2.5 % (compared to untreated fibers) Increase cellulose content: 87 % (up from 74 % in untreated fibers) Decrease hemicellulose and lignin content Better performance characteristics Higher thermal stability, tensile strength and strength	SenthilKumar, (2017)
Nanofibres	Hemp fibres	Alkali treatment and planetary ball milling, Composite preparation	Increase the thermal stability of epoxy	Rana and Gupta, (2018)
Lignocellulosic nanofibrils (LCNF)	Whole hemp plants	Bench-scale fibrillation (SMC)	Distinct nanoscale morphology at high fibrillation energy Crystallinity: 61.8 – 63,0 % (compared to Hemp 67.9 %) - hemp appear to remain plateaued in viscosity across all energy level	Lamm et al., (2024)
Nanofibers	Hemp fabrics	Repeated soaking cycles in an acidified waterglass solution followed by drying, ultrasonication, blending	- washing resistant - higher gel strength - enhanced viscosity - propensity to create web-like structures	Bifulco et al., (2020)
Nanofibrillated hemp fibers	Hemp bast fiber, shives and dust	High-shear grinder (for hemp fibers), TEMPO mediated oxidation (for hemp bast fibers), Ozonation (hemp shives)	The presence of long thin fibers usually leads to higher gel strength and increased viscosity	Immonen et al., (2018)
Nanofibers	Hemp fibers	Alkali treatment, mechanical treatment	Treatment reduces the fiber diameter from 40 μm to 30 μm The densities of composites are considerably reduced upon addition of hemp Stiffness of the composites increases as the fiber content increases	Pulikkalparambil et al., (2017)
Cellulose nanofibers	Hemp bast	Chemical treatment, cyrocrushing, mechanical treatment	Increase cellulose content to 94 % (± 1) from 76 % (± 4) and decrease lignin and hemicellulose	Bhatnagar and Sain, (2005)
Nanofibers	Hemp fibers agro-waste	Polyamide 6 + hemp fibers (PA6) electrospinning	Average diameter range: 10–60 nm - reduction of the sorption parameter by 60 % - higher tensile strength - higher toughness	Viscusi et al., (2023)
Lignocellulose nanofibers	Hemp stem and fiber	Alkali treatment, dissolution, electrospinning, coagulation	- Crystallinity degree → 58.6 %–62.2 % (by peak area), 60.4 %–69.6 % (by peak height) Reduction lignin content resulted: - uniform diameter of fibers - lower thermal stability	Kang et al., (2013)
Nanofibers	Hemp seed	Acetone/acetic acid electrospinning	- reduced fiber diameter - greater crushing and tensile strength	Tipu et al., (2022)

(continued on next page)

Table 1 (continued)

Type of nanotechnology	Source	Method of obtaining	Characterisation/methods	Ref
Cellulose microfibrils	Hemp fibres and shives	Steam explosion treatment, high-intensity ultrasonication technique (HIUS) and hydrothermal and alkali treatment	- diameter of hemp fibers → 20–700 nm (average value → 125 nm) - diameter of shives → 9–60 nm (average value → 24 nm)	Sutka et al., (2013)
Lignocellulose nanowhiskers (lcnws)	Hemp shives	Steam explosion, alkali treatment, ball milling, ultrasonication Electrospinning of nanofiber web composite PVA/lcnws	The presence of LCNWs: - reduced fiber diameter - higher tensile strength and lower stress at break	Sutka et al., (2015)
Nanofibers	Hemp fibres	Alkali treatment and stem explosion	- higher crystallinity index - improvement of surface appearance - reduced fiber diameter	Sutka et al., (2013)
Cellulose nanocrystals	Hemp agro-waste	Ammonium persulfate (APS) oxidation	- length → 183.1 (± 73.9 nm - purified CNCs) and 202.0 (± 79.2 - unpurified CNCs) - diameter of 2–6 nm - maximum loading forces → 6.20–6.38 nN - adhesion energy → 1.57 ± 1.12e–16 J	Heacock et al., (2024)
Hemp microfiber-based aerogel	Hemp bast fibers, hemp stalks	Top-down defibrillation method; freeze drying; hydrophobization of the obtained aerogels by chemical vapor deposition	Crystallinity: 68 % (for delignified hemp fibers: 74 %) Morphology of the hemp microfiber-based aerogel: - Low thermal conductivity - Superplasticity (at –173°C) - Aerogels demonstrate isotropic superelasticity - Aerogels have high porousness - Aerogels have reduced water affinity	Zhu et al., (2023)
Cellulose nanocrystals (CNC)	Hemp agrowaste	Alkaline pretreatment and acid hydrolysis; enzymatic pretreatment and acid hydrolysis; one-step oxidation method using APS	CNCs exhibit antimicrobial properties	Bhattacharjee et al., (2022)
Microfibrillated cellulose (MFC)	Hemp fibers	Chemi-physical, enzymatic and mechanical treatment	Average diameter: 29.5 nm Nanocellulose size of less than 1 μm Increase the degradation temperature	Dhandapani and Sharma, (2014)
Nanofibers	Hemp agro-waste	Chemi-mechanical defibrillation and mechanical defibrillation	- Increasing α-cellulose content by 37.96 %, a decrease hemicellulose content by 22.95 % and lignin content by 19.57 % - higher polymerization degree - higher thermal degradation temperature Longer defibrillation time: - smaller nanofibers - greater homogeneity of nanofiber size - lower polymerization degree - lower thermal degradation temperature	Pacaphol and Aht-Ong, (2017)
Nanofibers	Hemp fibers	Chemical treatment (pre-treatment, acid hydrolysis, alkaline treatment and bleaching) and mechanical treatment (cyro-crushing and high-pressure defibrillation)	Crystallinity: 71,2 % (increase from 57.4 % in untreated fibers) - α – cellulose: 94 % (up from 75 % in untreated fibers) - lignin and hemicellulose content combined: 4,3 %	Wang et al., (2007)
Nanofibers	Fibers	Ultrasonic technique (20 khz)	- great strength - great flexibility - biodegradability - biocompatibility	Zhao et al., (2007)
Nanofibers	Hemp stems	Electrospinning with polyacrylonitrile (PAN) and N, N-dimethylformamide (DMF), milling treatment	Thickness depends on deposition time and voltage, ranging from 30 to 250 nm. - The deposition time increases, thickness and density of nanofibers rise notably - The hemp stem nanofibers are more enduring compared to PAN polymer nanofibers at high temperatures	Erbasti et al., (2022)
Lignocellulosic nanofibrils (LCNF) Lignocellulosic microfibrils (LCMF)	Industrial hemp straw	Alkaline peroxide pulping, refining, PAA pretreatment, mechanical treatment (blending and sonication), centrifugation	- low delignification (only 36 %) - hemp lignin is more difficult to remove - higher CD values of LCNF	Pascoli et al., (2023)
Cellulose nanofibers	Hemp fiber	Drying, alkali and steam explosion treatment, bleaching, acid treatment	Increase cellulose content from 64 % to 95 % and decrease lignin and hemicellulose - Increase crystallinity - Increased composites' mechanical properties (hardness, tensile, strength, toughness)	Singh et al., (2021)
Cellulose microfibrils/nanocrystals/nanofibrils (CMF/CNC/CNF)	Hemp agro-waste	Alkali and bleaching treatment (CMF) Acid treatment and sonication CMF (CNC) TEMPO oxidation catalyst (CMF) and mechanical treatment (CNF)	PVA matrix with CNF: - homogenous dispersion - high crystallinity index - greater mechanical properties - higher tensile strength	Kassab et al., (2020)

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Table 1 (continued)

Type of nanotechnology	Source	Method of obtaining	Characterisation/methods	Ref
Cellulose nanocrystals or nanofibers	Hemp textile fiber refinery waste	Alkali treatment, Bleaching, Acid hydrolysis, Centrifugation, Dialysis, Homogenization	Increase crystallinity from 73 % to 86.1 % Removed non-cellulosic components - higher thermal stability - higher storage modulus - greater tensile shear adhesive - greater impact strength	Padinjakkara et al., (2020)
Cellulose nanofibers	Hemp fiber	Chemical (pre-treatment, acid hydrolysis, alkaline treatment) and mechanical (cyrocrushing, high pressure defibrillation) treatment	Diameters 50–100 nm, aspect ratio 87.5 - increase the yield strength - increase the tensile strength	Wang and Sain, (2007)
Microfibers	Bast hemp fiber	Mixed with molten PCL in a twin-crew extrusion machine	Low degradation temperature: ~230°C Increased thermal conductivity - the composite exhibit higher maximum hardness, elastic modulus, elastic work and thermal conductivity	Dhawal et al., (2020)
Nanocellulose	Hemp fibers	Alkaline-acid chemical treatments, mechanical grinding	- changes in thermal conductivity of samples Crystallinity range: 80.95 %, crystallite size: 5.41 nm High thermal stability: Major degradation at 361–370°C Hemicellulose and lignin degradation Antibacterial activity: <i>E. coli</i> higher sensitivity, <i>Bacillus</i> bacteria lower sensitivity Highest crystallinity index and crystallite size were observed for nanocellulose Higher crystallinity correlates with improved tensile strength, stiffness and rigidity	Rana and Gupta, (2020)
Nanofibers	Hemp fibers	shearing, combined heating and chemical processes	The nanocellulose fibers from acid process are shorter (~47.3 nm) than that from alkaline process (~ 54.2 nm). - higher crystallinity level - higher temperature = higher flexibility of fibers	Fan et al., (2011)
Cellulose nanofibers	Hemp stalks	Chemo- mechanical method: Alkali treatment, acid treatment and mechanical grinding	Improved results compared to the epoxy matrix: - Tensile strength: 52.17 % - Flexural strength: 48.17 % - Impact strength: 89.08 % - Hardness: 15.67 %	Rana and Gupta, (2021)

molecules, which are located in the trichomes. They are divided into 10 subclasses, with the most notable compounds being Δ^9 -tetrahydrocannabinol (THC), cannabidiol (CBD), cannabichromene (CBC), and cannabigerol (CBG). Regarding the terpenoids, over 200 have been identified in the leaves, flowers, and trichomes, with the most important being limonene, myrcene, and pinene (Addo et al., 2021; Lowe et al., 2021).

Some of the oldest archaeological evidence of human use of *C. sativa* as a fiber plant has been associated with its use in rope and textile production (e.g., plaited basketry) in Paleolithic sites in the Czech Republic, and other parts of Central Europe (Adovasio et al., 1996). Even today, it is used to produce fishing nets (Savo et al., 2013). Its medicinal use likely began after the accidental discovery of its psychoactive properties (Clarke and Merlin, 2013), and was widespread 5000 years ago. In its regions of natural origin, the plant was associated with religious rituals; for example, it was used to facilitate meditation in Hinduism and Tantric Buddhism. According to some Old Testament texts, it was used as incense and holy oil (Holland, 2010; Schultes and Hofmann, 1992). As a medicinal plant, it appears in the works of Chinese Emperor Chen Nung (Abel, 1980), in Egypt on the Ebers Papyrus (Epstein, 2010), and in Assyria on clay tablets (Scurlock and Andersen, 2005). Its use continued in ancient Greece and Rome, with references from Herodotus, Diodorus Siculus, and Galen (Butrica, 2014; Carod-Artal, 2013; Ryz at al., 2017).

Nanotechnology is a field dedicated to the study, production, and application of materials at the nanoscale. Among its most significant innovations are nanoparticles. These are no longer limited to serving as drug carriers (Saif et al., 2024), but also find applications as nanosensors (Liang et al., 2024), biopesticides, tools for enhancing agricultural productivity (Ullah et al., 2024), and solutions in environmental

protection (Biswas and Wu, 2005; Ealia and Saravanakumar, 2017; Zhan et al., 2024). Another groundbreaking technology is nanofiber production. These materials are characterized by their porosity and large surface area, making them suitable for use in filtration processes, insulating materials, and the production of practical goods such as clothing and supercapacitors. With each passing year, the range of applications for nanotechnology expands, and applied research facilitates the rapid industrial adoption of innovations (Huang et al., 2003; Tan and Lim, 2006). In the face of global warming and the need for sustainable development, there is considerable effort to seek eco-friendly sources of nanotechnology materials. Due to its tremendous potential, *C. sativa* has become an obvious target for exploration (Raihan and Bijoy, 2023); the plant is rich in secondary metabolites for producing nanoparticles or nanoemulsions, as well as cellulose and various derivatives, which can be employed in nanofiber production. Moreover, industrial and agricultural waste from hemp can be used to support green synthesis and the no-waste approach (Ahmadi and Lackner, 2024; Lorenzo et al., 2022; Vávrová et al., 2022).

Hence, the abundance of compounds and its unique properties make *C. sativa* an valuable resource with untapped potential for industrial, medical, and environmental applications. It is, therefore, no surprise that interest in its nanotechnologies is growing. This study reviews the current state of research and the possibilities of the application of hemp in nanoparticles, nanofibers, and nanoemulsions.

2. Study design

This review includes recent studies on the application of *Cannabis sativa* in various nanotechnological solutions. The studies are categorized according to their potential commercial sector. Research involving

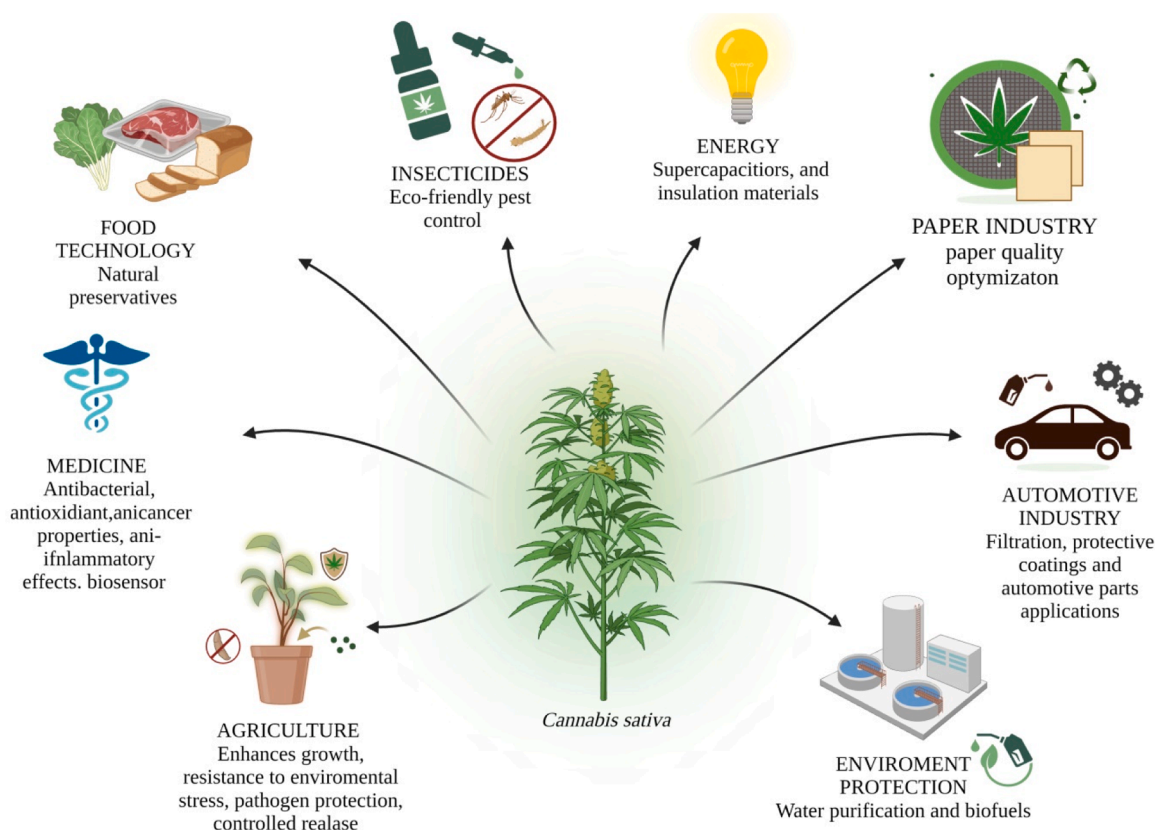


Fig. 1. Use of *Cannabis sativa* (L.) as a source of nanofibers/nanocellulose in industry (Created with BioRender.com).

other plants from the *Cannabaceae* family or studies using only isolated pure compounds without specifying the extraction and/or synthesis methods were excluded. This literature review was conducted using the following databases: PubMed, Web of Science, Google Scholar, and SCOPUS. The search strategy included the as follows terms (MeSH) “*Cannabis sativa*”, “*Cannabis sativa* extract”, “*Cannabis* oil”, “hemp”, “nanoparticles”, “nanofibers”, “nanoemulsions”, “nanocapsules”, “nanotechnology”, as well as “obtaining *Cannabis*-based nanofibers”, “Use of *Cannabis sativa* extract for green synthesis of nanoparticles”. The same approach was applied across all databases, with modifications made as needed to align with each platform’s requirements.

3. *Cannabis sativa* as a source of nanofibers and nanocellulose

3.1. *Cannabis sativa* provides nanocellulose and nanofibers for nanopaper production

Nanocellulose nanofibres are a unique material with exceptional properties such as high mechanical strength, light weight, biodegradability and the ability to be chemically modified. Nanocellulose, the source of these nanofibres, is mainly derived from plant biomass such as wood, bamboo, cotton or agricultural waste. It also has great potential for the development of sustainable technologies that combine advanced technical properties with environmental protection (Norfarhana et al., 2024).

C. sativa has various applications as a raw material in the paper industry. It is particularly useful for optimizing paper quality due to its compatibility with various cellulose and/or nanocellulose technologies. Filipova et al. demonstrated that hemp soda fibers (HF) are excellent for enhancing paper derived from waste fibers, with the resulting paper exhibiting the highest durability; its strength was further enhanced with the use of ammonium persulfate-oxidized cellulose nanofibrils (CNF). Additionally, the products obtained were compostable, which is

significant for environmental sustainability (Filipova et al., 2023). Platnieks et al. produced hemp nanopaper impregnated with vegetable oil acrylate such as acrylated epoxidized soybean oil or acrylated rapeseed oil. The final product offered suitable fiber surface wettability, viscosity, tensile strength, and storage modulus for replacing epoxy/paper composite insulators (Platnieks et al., 2023). Similarly, Aguado et al. produced nanocellulose from hemp pulp fibers by exploiting the strong adsorption of poly(diallyldimethylammonium chloride) on cellulosic fibers. The resulting paper exhibited reduced air permeability and a 57 % increase in tensile index, even without the use of a retention agent (Aguado et al., 2022). Vacche et al. extracted hemp-based nanocellulose from the by-products of hemp cultivation. The material was treated with NaOH and HCl and the resulting fibres were refined in a beater, treated with cellulase enzymes and mechanically defibrillated with an ultra-fine friction grinder. The properties of the resulting paper were comparable to those of paper made from wood pulp with rod-like nanofibrils (Dalle Vacche et al., 2021). Other examples of technological applications of *Cannabis sativa* are shown in Table 1 below; while the various industries using nanofibers obtained from *Cannabis sativa* are shown in Fig. 1.

3.2. Use of nanofibers from *Cannabis sativa* for filtration process and coating formation

Owing to their distinct physical and chemical characteristics, materials based on *Cannabis sativa* show considerable potential in ecological solutions for wastewater filtration. Hemp fibres, a biodegradable and renewable raw material, are particularly valued for their porous structure, high specific surface area and ability to adsorb various contaminants (Manaia et al., 2019; Mariz et al., 2024). Karaduman et al. employed electrospinning to produce cellulose acetate and cellulose nanofibers derived from hemp. The cellulose acetate fibers demonstrated significant adsorption properties, by effectively removing

methylene blue, indicating their potential use as environmentally-friendly adsorbents in water filtration processes (Karaduman et al., 2024). Similarly, Ullah et al. found *Cannabis sativa*-based materials to have significant potential for eco-friendly wastewater filtration applications. They report that nanofibrous webs based on hemp-derived carbon and polyacrylonitrile exhibited favorable adsorption for heavy metals, viz. 54 mg/g for nickel, 87 mg/g for cobalt, and 96 mg/g for copper (Ullah et al., 2023).

Jianyong et al. compared the engine oil filtration properties of various types of spunlaced nonwoven materials (hemp/cotton, hemp/viscose, hemp/viscose impregnated with polyacrylic adhesive), hemp woven fabric, PA6 nanofibers, and other two-layer/multi-layer composite nonwovens. The results showed that composite nonwovens containing PA6 nanofibers exhibited superior filtration performance, higher pressure drops, and smaller pore diameters, weights, and thicknesses, suggesting their potential use as filtration materials, particularly in the automotive industry (Jianyong and Jianchun, 2015).

Kumar et al. combined hemp-derived cellulose nanofibers with graphene nanosheets to reinforce castor-oil-based polyurethanes. Mechanical qualities enhanced by more than 400 %, while the addition of 1 % hemp nanofibers and graphene nanosheets increased the peak degradation temperature and glass transition temperature by 24°C and 36°C, respectively. Additional benefits, such as reduced surface energy, decreased adhesion work, and minimized phase separation, confirm the potential of these materials for protective coatings and automotive parts (Kumar et al., 2022).

Tyagi et al. utilized hemp hurd waste to extract cellulose nanofibers containing lignin, which were used to produce films/coatings with reduced polarity, low hydrophilicity, and a higher water contact angle. They found that water vapor permeability depended not on lignin content but on film density. These findings support the use of hemp hurd waste for coatings in industrial applications (Tyagi et al., 2021).

Lastly, Bieluns et al. converted hemp biomass waste into nanofibrillated cellulose foams with thermal performance ranging between 34–44 mW/m·K, suggesting their excellent suitability as insulation materials (Beluns et al., 2021). *Cannabis sativa*-based materials hence have great potential to become a pillar of sustainable filtration technology, combining efficiency with environmental protection. The introduction of such solutions could significantly reduce the negative impact of industrial and municipal wastewater filtration on ecosystems.

3.3. Use of *Cannabis sativa* nanofibers for the production of bionanosensors

Bionanosensors are advanced analytical devices that combine biology with nanotechnology to accurately detect and analyse various chemical, biological or physical substances. They are used in a wide range of fields, including medicine, environmental protection, agriculture and the food industry. The integration of nanocellulose with nanoparticle technology presents intriguing possibilities, leading to nanocomposites with enhanced application potential (Golmohammadi et al., 2017; Li et al., 2022). This approach was demonstrated by Phumma et al., who combined hemp-derived nanocellulose with silver nanoparticles to create a nanosensor with improved electrochemical lactate detection. Nanocellulose was chemically extracted from hemp fibers, and silver nanoparticles were incorporated through a self-reduction process. The nanomaterial obtained from the integration of nanofibers and nanoparticles was combined with poly(vinyl alcohol), resulting in a composite with enhanced thermal stability up to 450°C. This nanocomposite was then used to modify a graphene electrode through a screen-printing process. The sensor showed an increase in current signal proportional to lactate concentration (linear range: 0–25 mM, with a cutoff value of 12.5 mM), enabling the development of a wearable biosensor capable of detecting muscle fatigue (Phumma et al., 2023). Tiwari et al. also developed a *Cannabis sativa*-based bionanosensor in the form of a carbon dot co-doped with nitrogen and

sulfur (N-S@CsCD), exhibiting excitation-independent emission behavior with a peak wavelength around 414 nm. This nanosensor was stable across variations in time, pH, and salt concentration, and displayed a reversible, temperature-responsive fluorescence "turn-off" behavior. Furthermore, vitamin B12 induced a fluorescence "turn-off" with a detection limit of 7.87 µg/mL. The bionanosensor demonstrated excellent biocompatibility, high cell viability, and was non-toxic, making it a promising tool for bio-detection applications (Tiwari et al., 2019).

3.4. *Cannabis sativa* provides cellulose nanofibers to support agriculture

The combination of *Cannabis sativa* nanofibres with encapsulation technology is an innovative approach to agriculture that can increase efficiency and sustainability. This approach is in line with the concept of sustainable agriculture, which offers modern, environmentally-friendly solutions to support agricultural productivity while reducing environmental impact. In a study by Kaur et al., hemp stalks were used as a source of cellulose nanofibers, which were converted into carboxymethyl cellulose and subjected to cross-linking to produce a three-dimensional aerogel, which in turn was used to encapsulate urea and ammonium dihydrogen phosphate. The gel has been evaluated for improving soil health through long-term nutrient release. The percentage nutrient release was 48.4 % (40 hours in water) and 62.28 % (120 hours in soil) for the urea capsules and 44.46 % and 56.62 % for the ammonium dihydrogen phosphate. The release kinetics for both fertilizers followed the Higuchi model and Fickian diffusion, indicating controlled nutrient release (Kaur et al., 2023). This approach not only offers an innovative method for managing agricultural waste but also presents promising technology for crop cultivation.

3.5. *Cannabis*-based nanofibers in supercapacitor manufacturing

Supercapacitors, also known as ultracapacitors, are energy storage devices that combine the properties of both conventional capacitors and batteries. They are becoming increasingly important in sustainable energy technologies because of their reliability and low degradation. Nanocarbon derived from *Cannabis sativa* has shown great potential for use in supercapacitors. Wang et al. utilized hemp bast fibers to produce graphite nanosheets (10–30 nm thick), with a high specific surface area, up to 2287 m²/g, and a mesoporosity volume fraction of 58 %. This unique material proved suitable for ionic-liquid-based supercapacitors operating across a wide temperature range. At 0°C and a current density of 10 A/g, the electrode maintained an impressive capacitance of 106 F/g. Under an extreme current density of 100 A/g, the specific capacitances were 113, 144, and 142 F/g at 20°C, 60°C, and 100°C, respectively. The maximum energy density achieved was 12 Wh/kg, surpassing commercially-available supercapacitors (Wang et al., 2013).

Jiang et al. evaluated the potential of hemp straw activated carbon (HSAC) produced via a hydrothermal process followed by pre-oxidation and KOH-assisted carbonization. The optimized material exhibited abundant porosity and excellent capacitive properties, with a specific capacitance of 279 F/g at a current density of 0.5 A/g. After 5000 charge-discharge cycles at a current density of 2 A/g, the material retained 91.6 % of its capacitance. Electrodes made from HSAC enabled the construction of a symmetrical supercapacitor that successfully powered an LED light (Jiang et al., 2019a). In another study, carbon nanofibers were obtained through the electrospinning of liquefied bio-stalk carbon mixed with polyacrylonitrile. The carbon was derived from *C. sativa* straw through a straightforward chemical treatment process. The resulting nanofibers exhibited comparable electrochemical properties, as demonstrated in similar research by Shi et al. (2019), (Jiang et al., 2019b).

In contrast, Li et al. used lignocellulosic nanofibers as nanofillers in polyacrylic acid gel electrolytes (PAA/DES) integrated with lignin-silver nanoparticles. The resulting material displayed exceptional properties,

Table 2
Application of *Cannabis sativa* (L.) with nanofibers in food technology and medicine.

Source	Type of nanotechnology	Model drug	Strain MIC/ microorganism/ parasite	Cell line/ in vivo/in vitro	Effect	Ref.
<i>Cannabis sativa</i> stalks	HS-CMC/PVA hydrogel	Norfloxacin (NFX)	<i>S. aureus</i> , <i>E. coli</i> Showed growth suppression zones of 16.4 ± 0.4 mm and 19.2 ± 0.3 respectively	Phosphate buffer and 37°C temperature to simulate gastrointestinal conditions	Effective for sustained release of Norfloxacin, antibacterial effect, effective drug release at pH 1.2 (91 %) and 7.4 (82 %), swelling ratio (538.7 %) at pH 7.4 and (378.4 %) at pH 1.2	Sethi et al., (2022)
<i>Cannabis sativa</i>	Micro/nanofiber film with a sandwich-like structure (PLA-PVA-PLA) as a diabetic wound dressing	Metformin hydrochloride, Puerarin, Erythromycin	<i>S. aureus</i> , <i>E. coli</i> Showed growth suppression zones of 55.84 mm and 55.10 respectively	L929, Wounds of diabetic rats (SPF-grade Sparague-Dawley rats)	Mechanical properties resemble human skin, antibacterial effect, biocompatible, not affect the growth and propagation of L929 cells, 91.11 % closure in diabetic mice wounds, less inflammation and thicker granulation in diabetic wounds,	Liao et al., (2023)
<i>Cannabis sativa</i> Agro-waste	Nanofibers composite (HW-DESS_PVA)	-	<i>S.aureus</i> and <i>K.pneumoniae</i> . Exhibited growth inhibition zones from 60.68 ± 4.10 % to 99.72 ± 0.05 % (<i>S.aureus</i>) and 50.65 ± 1.14 % to 54.94 ± 3.42 % (<i>K.pneumoniae</i>).	<i>S. aureus</i> <i>K. pneumoniae</i>	Antibacterial effect, antioxidant activity, biocompatibility, natural absorbency	Mouro et al., (2024)
<i>Cannabis sativa</i> stalks	Nanocellulose composite films (electrospun)	-	-	Rat Schwann fibroblasts cell (RSC 96)	- Improve cell adhesion, growth and retention - improving biocompatibility	Zhang et al., (2023)
<i>Cannabis sativa</i>	Bionanocomposites à poly (latic-co-glycolic acid/ nano hydroxyapatite)/ hemp oil PLGA/nHAp/Ho	-	<i>S.epidermidis</i> , <i>E.coli</i> The inhibition zone diameter (>20 mm)	Osteoblast cells (MC3T3-E1), <i>Escherichia coli</i> , <i>Staphylococcus epidermidis</i>	Antibacterial effect and wound healing. Composite improved cell density	Ciftci and Özarslan, (2024)
<i>Cannabis sativa</i>	Electrospun acetate-based nanofibers with hemp extract/seed oil	Cannabis oil-extract	<i>S.aureus</i> . Exhibit growth inhibition rates reached 99.3 % for full-spectrum hemp extract and 85.3 % for cold-pressed hemp seed oil	<i>Staphylococcus aureus</i> (MSSA, ATCC #6538)	The greatest antibacterial activity against <i>Staphylococcus aureus</i> was observed with full-spectrum hemp extract.	Wagner-Graham et al., (2019)
<i>Cannabis sativa</i>	A composite micro-nanofiber membrane containing hemp plant actives (tannic acid) silver nanoparticles (AgNPs) and polyacrylonitrile (AN)	Plant actives	Showed growth suppression rates against <i>E.coli</i> reached 73.08 % ± 3.14 % (0.03 kg/L) and 79.67 % ± 1.62 % (0.05 kg/L). Showed growth suppression rates against <i>S. aureus</i> reached 95.15 % ± 1.19 % (0.01 kg/L); 97.91 % ± 1.62 % (0.03 kg/L) and 98.29 % ± 0.90 % (0.05 kg/L)	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> .	The composite micro-nanofiber membranes exhibit good antibacterial properties against both <i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	Dongsong et al., (2023)
<i>Cannabis Sativa</i> Hurd shives	Nano-fibrillated cellulose (LNFC)	Ethanol extracts from emp hurd	<i>E.coli</i> Exhibited growth inhibition zones of 1.85 mm and reduction in bacterial count (CFU)	-	The high efficacy in inhibiting <i>E. coli</i> , achieving a 99.7 % reduction in bacterial count (CFU)	Tyagi et al., (2022)
<i>Cannabis sativa</i> Organosolv hemp pulp form hemp fibers	Nanocellulose	-	-	-	Improving the quality of food packaging paper by enhancing its mechanical (tensile strength up to 66.7 MPa, breaking length increased by 42 %) and increasing crystallinity (87.2 %)	Barbash et al., (2022)
<i>Cannabis sativa</i> trunks	Nanocellulose suspension	-	-	In situ (spinach)	Nanocellulose-coated leaves coated showed better appearance and chlorophyll preservation, along with a 50–70 % reduction in the respiration	Pacaphol et al., (2019)

(continued on next page)

Table 2 (continued)

Source	Type of nanotechnology	Model drug	Strain MIC/ microorganism/ parasite	Cell line/ in vivo/in vitro	Effect	Ref.
<i>Cannabis sativa</i>	PLA nanofibrous composite film with hemp fibers	Ag ₂ O	Fungi and bacterial strains: <i>A. niger</i> , <i>Penicillium</i> , <i>S. aureus</i> , <i>E. coli</i>	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Aspergillus niger</i> , <i>Penicillium</i> , mouse fibroblast cell line (L929)	rate on the fresh-cut spinach The PLA nanofiber composite film showed great biocompatibility, antibacterial and antifungal activity. Good air permeability and biodegradability.	Liao et al., (2023)
<i>Cannabis sativa</i> Hemp inflorescences	Active PVA nanofibers film loaded with hemp extract	Hemp extract (cannabinoids, phenolic acids, flavonoids)	<i>L. monocytogenes</i> , <i>S. enterica</i> .	In situ (raw poultry storage)	Antibacterial effect: control reached 10.5–10.7 log CFU/mL, treated samples reached 9.5–8.87 log CFU mL), Bacteriostatic effect: Prevent further growth of <i>S. enterica</i> during 4 days (storage at 25°C)	Dudley et al., (2023); Dudley et al., (2024);

including strains exceeding 1000 % and compression strengths over 1000 kPa. This material was used to build a supercapacitor with a high specific capacitance (271 F/g at a current density of 0.5 A/g), achieving nearly 100 % capacity retention after 3000 cycles (Li et al., 2024). Hence, nanomaterials derived from hemp possess remarkably large surface areas, excellent conductivity, and structural stability, making them highly effective for the production of energy storage devices.

3.6. Hemp nanofibers in food technology and medical use

In addition to the uses described above, hemp nanofibers are used in medicine and food processing. Some studies using nanofibers and nanocellulose composites and their biological properties are presented below in Table 2.

4. Nanoparticles

4.1. Nanoparticle technology in the context of agriculture and *Cannabis sativa* cultivation

A key area where advancements in nanotechnology are being actively implemented is agriculture, with nanoparticles already used as elicitors or biopesticides. In the context of *Cannabis sativa*, nanoparticles can be used to enhance it as an industrial crop, or *C. sativa* itself can be used as a source for synthesizing new nanoparticles with broad agricultural applications through green synthesis. In 2021, Feizi and Javedanipour demonstrated that the combination of TiO₂ nanoparticles and magnetic fields not only stimulated hemp growth but also improved its morphological and physiological properties (Feizi and Javedanipour, 2021). Similarly, Deng et al. showed that Fe₃O₄ nanoparticles, applied at varying concentrations, increased the fresh and dry biomass of hemp tissues as well as their length; their findings research also revealed an elevation in photosynthesis-related metabolites and a reduction in tetrahydrocannabinol (THC) content (Deng et al., 2022).

Notably, the impact of nanoparticles on secondary metabolite levels varies with the variety of *C. sativa*. For instance, Cahull et al. found that CuO nanoparticles were more effective in enhancing THC and CBD production in the Wife variety compared to Merlot (Cahill et al., 2024). An intriguing application of nanoparticles in hemp cultivation was proposed by Guerriero et al., who developed a nano-biostimulant using hydrolyzable porous silicon nanoparticles stabilized with saccharide trehalose, containing various combinations of lipids and amino acids. Dubbed the "phyto-courier" by the authors, this technology was applied as a foliar spray to salt-stressed hemp plants. It enabled the delivery of quercetin to the leaves, alleviating stress symptoms. This eco-friendly technology could prove invaluable for cultivating plants under current

climate change conditions (Guerriero et al., 2021).

Increased growth has also been achieved in hemp using sulfur nanoparticles synthesized via green methods, involving *C. sativa* leaf extracts and sodium thiosulfate pentahydrate (Na₂S₂O₅·5H₂O). The use of these nanoparticles resulted in a 30 % biomass increase, 50 g fresh weight gain, 20 g dry weight gain, 90 cm increase in shoot length and 28 cm increase in root length (Dasauni et al., 2024).

Furthermore, hemp-derived nanoparticles can support the growth and cultivation of other crops while serving as eco-friendly biopesticides. Kumar et al. synthesized silver nanoparticles from fresh *C. sativa* leaves. Tomato seeds treated with the nanoparticles germinated faster and exhibited lower mortality compared to untreated seeds. These nanoparticles also reduced the incidence of diseases caused by the fungus *Fusarium oxysporum* by altering root exudates and triggering stress hormone release (Kumar et al., 2023a, 2023b).

Similarly, Karmous et al. used zinc and copper nanoparticles synthesized from hemp leaves as bio-nanofungicides. Applied as foliar treatments on soybean (*Glycine max* L.), the nanoparticles not only enhanced plant growth and nutrient content but also improved the antifungal defense mechanisms and photosynthesis efficiency (Karmous et al., 2023). The effect of nanoparticles on growth and germination can, however, be concentration-dependent. For instance, Nienu and Devashree synthesized FeO nanoparticles using *C. sativa* leaf extracts. At lower concentrations, these nanoparticles promoted the germination and growth of *Vigna radiata*, an important crop, whereas higher concentrations inhibited these processes (Nienu and Devashree, 2019).

Another interesting eco-friendly biopesticide based on the biological activity potential of *C. sativa* was developed by Menossi et al. The authors created Solid Lipid Nanoparticles (SLNs) coated with hemp extract and chitosan which exhibited significantly stronger antifungal activity against *Fusarium solani* sp. Eumartii compared to the pure extract alone (Menossi et al., 2024). These studies highlight the significant potential of *C. sativa*-derived nanoparticles in offering eco-friendly solutions for sustainable agriculture by improving crop growth, resistance to environmental stress, and defense against pathogens.

Finally, it is worth noting that nanoparticles can also serve as an effective tool for genetic modification of *Cannabis sativa*, as demonstrated by in a study of gold nanoparticles coated with silica dioxide co-grafted with two soybean transcription factors. This approach enabled the transcription of soybean genes in the hemp leaf cells, including the trichome cells, where key secondary metabolites such as terpenes and cannabinoids are synthesized (Ahmed et al., 2021).

4.2. *Cannabis sativa*-based nanoparticles in environmental protection

Hemp can also be utilized for the green synthesis of nanoparticles,

Table 3
Application of *Cannabis sativa* (L.) extract with nanoparticles in food technology and medicine.

Source/ Extract	Nanoparticles/ micocapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
<i>Cannabis sativa</i> oil extract	Silver nanoparticles (AgNPs), the hydrogels Col-CS-AgNPs,	Oil extract of Cannabis sativa 0.150 mL	-	MDCK epithelial cell line	Mechanical properties improved and resistance to collagenase degradation, antimicrobial effect of the nanocomposite against <i>Staphylococcus aureus</i> and <i>Pseudomonas aeruginosa</i> (long-lasting), antioxidant activity, very strong scavenger activity of the (DPPH) radical, reduced the concentration of ROS, oxidative stress decreased, stimulated cell proliferation	Antezana et al., (2021)
<i>Cannabis sativa</i> roots extract (ethanolic)	Silver nanoparticles (AgNPs)	Concentration → 100 µg/mL (antioxidant potential), Concentration → 500 µg/mL (cytotoxicity in HEK 293 cells),	<i>K. pneumoniae</i> , <i>E. coli</i> , <i>P. aeruginosa</i> , <i>S. aureus</i> The minimum inhibitory concentration of AgNPs against Gram-positive –65 µg/mL, Gram-negative bacteria- from 60 µg/mL to 75 µg/mL	HEK 293 cell culture,	Antibacterial- against <i>S. aureus</i> , <i>P. aeruginosa</i> , <i>K. pneumoniae</i> , and <i>E. coli</i> , antioxidant potential, scavenged free radical, AgNPs- lower cytotoxicity revealed (cell viability was observed: 52.38 ± 0.6 %) at a very high concentration in HEK 293 cells, less haemolytic potential of silver nanoparticles,	Suman et al., (2022)
<i>Cannabis sativa</i> - extract of stem separated from cortex and core [xylem part] (aqueous)	AuNPs and AgNPs- gold nanoparticles and silver nanoparticles from Cannabis sativa- fiber and core	C-AuNPs and C-AgNPs, 0.7, 4.5 and 3.6 mg/mL, presence of flavonoids, cannabinoids, phenols and terpenes	<i>E. coli</i> , <i>P. aeruginosa</i> and <i>S. epidermidis</i> MIC concentration- 6.25 and 12.5 µg/mL, the MBC concentration- 12.5 and 25 µg/mL against <i>P. aeruginosa</i> and <i>E. coli</i>	-	<i>P. aeruginosa</i> and <i>E. coli</i> biofilms inhibition	Singh et al., (2018)
<i>Cannabis sativa</i> Leaf extracts- varieties of three <i>Cannabis sativa</i> powdered leaves, aqueous extract	Silver nanoparticles (AgNPs)	AgNO ₃ 5 mM solution of 1:1- the best ratio of extract	<i>E. coli</i> , <i>K. pneumonia</i> and <i>P. fluorescens</i> , <i>S. aureus</i>	-	Superior than isolated extract antioxidant capacity, inhibition determined by the DPPH• and ABTS•+ assay, antibacterial activity against human pathogens	Csakvari et al., (2021)
<i>Cannabis sativa</i> - ethanolic extract	Bimetallic nanoparticles (AgAuNPs) produced from Cannabis sativa extract waste	10 % v/v of Cannabis sativa extract with a 1: 1 mM solution of tetrachloroauric acid and silver nitrate	Various strains of <i>P. aeruginosa</i> . Concentration range of inhibitory activity- 1.3–2 mg L ⁻¹ of silver and 2.2–3.4 mg L ⁻¹ of gold	-	Antimicrobial properties, activity against strains of <i>P. aeruginosa</i> - inhibited growth and biofilm formation	Michailidu et al., (2024)
<i>Cannabis sativa</i> - acetone extract	CBD-rich cannabis extract encapsulated in polymeric micelles formulation (CBD/ PMs)	CE with a 1:29 ratio (31.65 % CBD to 1.08 % THC (CE/ CBD))	-	Female Swiss albino mice (20–22 g)	Significant analgesic effect (chemical pain model), better stability encapsulated CE, more efficient- higher analgesic effect CBD/PMs than free CE, encapsulation improved stability and functionality	Román-Vargas et al., (2023)
<i>Cannabis sativa</i> leaves extract	Titanium dioxide nanoparticles (TiO ₂ NPs)	-	<i>S. aureus</i> , <i>E. coli</i> , <i>P. aeruginosa</i>	-	antimicrobial effect against Gram-positive and Gram-negative bacteria, higher against Gram-negative bacteria	Hafeez et al., (2021)

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Table 3 (continued)

Source/ Extract	Nanoparticles/ micocapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
<i>Cannabis sativa</i> - leaf extract	Bimetallic- Au–Ag nanoparticles (NPs)	250 µg mL ⁻¹ NP concentration- antiparasitic activity	<i>P. aeruginosa</i> , <i>B. subtilis</i> , <i>E. coli</i> , <i>K. pneumoniae</i> , and <i>Leishmania major</i> promastigotes	-	antibacterial and anti-leishmanial activity, potent antibiotic, enhanced antibacterial activity against <i>B. subtilis</i> and <i>P. aeruginosa</i> as compared to Au and Ag without nanoparticles	Abbasi et al., (2018)
<i>Cannabis sativa</i> - plant extract, methanol extract	Gold nanoparticles (Au-NPs)	(IC50: 171 ± 2.28 µg/ mL) of <i>Leishmania tropica</i>	<i>E. coli</i> , <i>B. subtilis</i> , <i>K. pneumoniae</i> , <i>S. aureus</i> , and fungal strains of <i>A. niger</i> , <i>A. flavus</i> <i>A. Solani</i> , and <i>A. niger</i> , 85E Strain of <i>Streptomyces</i> , the amastigote cultures of <i>Leishmania tropica</i> KMH23	-	Antimicrobial, antifungal, enzyme inhibition, leishmanicidal activity against amastigotes of <i>L. tropica</i> , brine shrimp lethality, protein kinase inhibition	Hameed et al., (2020)
<i>Cannabis sativa</i>	Silver nanoparticles (AgNPs)	-	<i>S. aureus</i> , <i>E.coli</i> , MIC concentration- 12.77 µg/mL, the MBC concentration- 25 µg/mL against both the pathogens	-	Antibacterial activity, strong potential against both Gram-positive and Gram-negative bacteria	Mandal et al. (2021)
<i>Cannabis sativa</i> L aqueous extract from leaf	Gold nanoparticles AuNPs	<i>Cannabis sativa</i> leaf aqueous extract (20 µg / mL)	-	Normal cell line- HUVEC, Acute lymphoblastic leukaemia cell line- MOLT–3, Acute lymphoblastic leukaemia cell line TALL–104 and J.RT3 -T3.5	Cytotoxicity, anti-acute leukemia, and antioxidant properties, chemotherapeutic drugs in treating of acute leukemia (various type), activation of p53	Chang et al., (2021)
Seed Extracts of <i>Cannabis sativa</i>	Silver nanoparticles- AgNPs with extract	Inhibition effect (100 %) at 375 µg mL ⁻¹ against the A549 lung cancer cell line, IC50 of 125 µg mL ⁻¹	<i>E. coli</i> <i>S. aureus</i>	A549 lung cancer cells, HaCaT-immortalized human keratinocyte cells,	Anticancer effects, high antibacterial effect, 280 % more effective against <i>E. coli</i> and 85 % against <i>S. aureus</i> bacteria than one of the ampicillin antibiotics, nanomedicines for the treatment of lung cancer	Yontar and Çevik, (2024)
<i>Cannabis sativa</i> - full-spectrum C. <i>sativa</i> ethanol extract	CN-PTEe nanoparticles- biobased poly (thioether-ester)- PTEe nanoparticles containing full- spectrum extract-CN	-	-	B16F10, T98, and U87- the cancer cell lines and the non-tumoral NIH3T3 cells	Reduced the viability of the cancer cell lines but not reduced the viability of the non-tumoral NIH3T3 cells, the AKT signaling pathway inhibited and autophagy induced in B16F10 melanoma cells, anticancer activity,	Freire et al., (2023)
seeds of <i>Cannabis sativa</i>	Biogenic Se nanoparticles (SeNPs)	Two mL of hemp seed extract to 10 mM sodium selenite with 30 mL of water Concentration of 1500 µg/mL	-	In vivo- hind paw edema model (Balb/C female mice)	Anti-inflammatory potential, redox modulatory	Meht a et al. (2021)
<i>Cannabis sativa</i> extract of plant's leaves (aqueous)	Zinc oxide nanoparticles (ZnONPs)	-	-	-	Antioxidant activity, effective for the removal of organic dyes	Shahzadi et al. (2020)
<i>Cannabis sativa</i> - leaf extract	Silver nanoparticles (SNPs)	5 mL of extract to 95 mL of aqueous 1 mM AgNO ₃	<i>E. coli</i> , <i>S. marcescens</i> , <i>S. aureus</i> and <i>B. subtilis</i> , <i>E. coli</i> , <i>K. pneumoniae</i>	-	better effect of mixing antibiotics with SNPs, antibacterial activity,	Singh et al., (2018)
<i>Cannabis sativa</i> - aqueous leaf extract (CSE)	Silver nanoparticles (AgNPs)	AgNO ₃ (3 Mm), 1:0.1 ratio of AgNO ₃ to CSE	<i>M. luteus</i> , <i>S. aureus</i> , <i>E. coli</i> , <i>B. subtilis</i> and <i>K. pneumoniae</i> bacteria, yeasts model <i>C. albicans</i> and <i>S. cerevisiae</i>	-	Antibacterial activity, anti-yeast and α-amylase inhibitory activities	Chouhan and Guleria, (2020)

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Table 3 (continued)

Source/ Extract	Nanoparticles/ micocapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
<i>Cannabis sativa</i> - callus extract (CE)	Green synthesis of ZnO and Ag-NPs nanoparticles	Various concentrations: 5/ 4/ 3 mg·mL ⁻¹ (Ag- NPs) and 4/5/ 10 mg·mL ⁻¹ (ZnO-NPs) antibacterial and antifungal, cytotoxicity at a concentration of 20 µM	<i>K. pneumonia</i> , <i>B. subtilis</i> , <i>S. aureus</i> , and <i>P. aeruginosa</i> , five pathogenic fungal strains: <i>A. niger</i> , <i>A. fumigatus</i> , <i>A.</i> <i>flavus</i> , <i>F. solani</i> and <i>Mucor</i> MIC ranges: 300–120 µg·mL ⁻¹	HepG2 cell line	Antibacterial and antifungal activities, cytotoxicity effect	Zaka et al., (2021)
<i>Cannabis sativa</i> - leaf extract	Palladium nanoparticles (PdNPs)	IC ₅₀ value: 22.17 µg/mL	Multi-drug resistant strains (MDR) <i>E. coli</i> , <i>S.</i> <i>abony</i> , <i>S. aureus</i> , and <i>K. pneumoniae</i> , Effective for MDR resistant bacteria- MIC (52.04–68.3 µg/mL)	Human lung cancer A–549 cells	Cytotoxic potential for cancer cells, management of lung cancer cells and MDR pathogens- clinical strains	Yaseen et al., (2023)
<i>Cannabis sativa</i> - leaf extract	Nanoparticles of palladium Pd-NPs, microparticles (Pd- MPs), Leaf extract of <i>Cannabis sativa</i> L. (CS–Pd-NPs) and Pd nanorods (Pd-NRs)	Concentration of 1 µg/ mL	-	Macrophage RAW 264.7 cell lines	Pro-inflammatory and cytotoxic effects on the <i>in- vitro</i> and <i>in-vivo</i> models, minimal rise in IL–6 cytokine and TNF-α levels	Nematullah et al., (2022)
<i>Cannabis sativa</i> - leaf extract	ZnO and Cu Nanoparticles, Mg, Ag-doped ZnO using <i>Cannabis sativa</i>	-	<i>P. aeruginosa</i> , <i>S. aureus</i> , MRSA (Methicillin- resistant <i>S. aureus</i>), <i>Salmonella typhi</i> , <i>K.</i> <i>pneumoniae</i> , <i>C. albicans</i> , <i>R. necatrix</i> , <i>Fusarium</i> sp.	-	Antimicrobial activity against: <i>P. aeruginosa</i> , <i>S.</i> <i>aureus</i> , MRSA (Methicillin- resistant <i>S. aureus</i>), <i>S.</i> <i>typhi</i> , <i>K. pneumoniae</i> , <i>C.</i> <i>albicans</i> , <i>R. necatrix</i> , <i>Fusarium</i> sp., Ag doped NPs- antimicrobial activity against various fungal and bacterial strains as compared to Mg/Cu doped nanoparticles	Chauhan et al. (2022)
<i>Cannabis sativa</i> - extract from hemp waste leaves	SiO ₂ -NP (nanoparticles) from industrial hemp waste	IC50 doses of SiO ₂ -NP in MCF7 and MDA- MB–231 breast cancer cells- 146.73 ± 7.54 and 54.93 ± 5.54	Gram-positive and gram- negative bacteria strains	MCF7 and MDA- MB–231 breast cancer cells	It showed antibacterial activity against both Gram-positive and Gram- negative bacterial strains, increased in the expression of apoptosis-related genes, corelated against AChE enzyme activity	Korkmaz et al. (2024)
<i>Cannabis sativa</i> - lyophilized dry methanolic extract	Nanostructured lipid carriers and nanoliposomes loaded with <i>C. sativa</i> extract	Concentration of 1 mg/ mL in methanol	-	<i>In vivo</i> - male ICR mice	Significantly higher antioxidant capacity compared to the alone extract, elevated the latencies for clonic, myoclonic and tonic seizures, anticonvulsant activity	Mihailova et al., (2022)
<i>Cannabis sativa</i> - leaf extracts	Copper-doped ZnO nanocomposites (Cu ₂ OZnONPs) mediated by the polyphenolic extracts of “wild” <i>Cannabis</i> <i>sativa</i>	Varying concentrations: 125/250/500/1000/ 2000 µg/mL, The IC50 values–120.5 µg/mL and 49.86 µg/mL for cannabis lyophilised extract and the Cu ₂ O- ZnONPs,	Pure cultures of <i>S. aureus</i> , <i>P. aeruginosa</i> , <i>E. coli</i> and <i>E. faecalis</i> The highest zone of inhibition - <i>E.</i> <i>faecalis</i> (500 mcg/mL)	-	Anti-inflammatory, antioxidant and antibacterial activity, better wild cleansing properties <i>C. sativa</i> , stable biocompatible nanostructures	Zengeni and Chifamba, (2024)
<i>Cannabis sativa</i> - seed oil	Nanostructured lipid carriers (NLCs)- Khellin-loaded-(K- NLCs)	Selected as liquid lipid, 3 % w/v of <i>Cannabis</i> <i>sativa</i> L. seed oil,	-	The colorectal adenocarcinoma cell line (Caco–2)	Increased intestinal absorption and solubility of khellin (increased khellin permeability more than two orders of magnitude by nanoparticles), - good biopharmaceutical characteristics for oral delivery - enhanced khellin’s bioavailability- enhanced therapeutic effects	Vanti et al., (2021)
Industrial hemp (<i>Cannabis sativa</i> L.)	Nanoparticles made by complexing hemp	30 % water phase and 70 % oil phase (v/v) composed, contained	-	-	Stronger short-range interactions between flocs	Chuang et al., (2020)

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Table 3 (continued)

Source/ Extract	Nanoparticles/ micocapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
	globulin (HG) with sodium caseinate (SC)	2 % protein, SC or HG-SC nanoparticles with an HG:SC ratio of 1:2/1:1			of oil droplets (resulted solid-like emulsion)	
<i>Cannabis sativa</i> -three different cannabis strains (methanol extract)	High cannabinoid content PLGA nanocapsules	Concentration of 5 µg/mL IS in the final solution	-	In vitro digestion simulation	High cannabinoid content of THC and CBD, therapeutic applications, lower cannabis extract recommended for a better performance of PLGA nanocapsules, improve mucoadhesiveness and mucopermeability	Villate et al., (2024)

which have wide-ranging applications in environmental protection. This is particularly important given the increasing pollution of natural ecosystems and global warming. These nanoparticles seem to offer particular promise in water purification processes, including wastewater and reservoir treatment. Dasauni et al., using UV–VIS spectral investigations, demonstrated that their *Cannabis sativa*-based sulfur nanoparticles could act as photocatalysts in the visible light spectrum, with potential applications in wastewater treatment (Dasauni et al., 2024). Similarly, a titanium dioxide nanoparticles synthesized using a cannabis leaf extract exhibited significant photocatalytic properties; it demonstrated an impressive 98.2 % degradation efficiency for methylene blue dye (BinSabt et al., 2022). Likewise, Naz et al. employed hemp leaf extract to synthesize monometallic (Fe, Mn) and bimetallic (Fe-Mn) nanoparticles. All nanoparticles induced photocatalytic dye degradation, but the bimetallic Fe-Mn nanoparticles were the most efficient, degrading ethyl orange and Congo red dyes in just 12 and 14 minutes, respectively (Naz et al., 2022). In addition, Fe₃O₄ nanoparticles synthesized by root extract from *Cannabis sativa* demonstrated high photocatalytic degradation efficiency against malachite green, achieving a degradation rate of 87.72 % (Rana et al., 2024).

Collectively, these studies confirm the immense potential of hemp in the green synthesis of nanoparticles, which can play a critical role in water purification. Also, nanoparticles can be used to transform hemp-derived agricultural materials and waste into biofuels. For example, Sawaira et al. produced biodiesel from *C. sativa* seed oil using Bi₂O₃ nanoparticles synthesized from *Euphorbia royleana* leaf extract via membrane reactors. The resulting biodiesel exhibited the following fuel properties: acid number 0.203 mg KOH/g, density 0.8623 kg/L, kinematic viscosity 5.32 cSt, flash point 80 °C, pour point –11 °C, cloud point –11 °C, sulfur content 0.00047 wt%, and carbon residue 0.2 (Sawaira et al., 2023).

4.3. Nanoparticles from hemp in food processing and medicine

Nanoparticles derived from cannabis also appear to offer as food processing, storage, and medical applications. For example, the aforementioned sulfur nanoparticles extracted from hemp exhibit antibacterial activity against Gram-positive *S. aureus* (MTCC737) and Gram-negative bacteria including *A. salmonicida* (MTCC1522), *E. coli* (MTCC443), and *K. pneumoniae* (MTCC3384), with the strongest effect observed against *E. coli* (Dasauni et al., 2024). In addition, nanoparticles from *C. sativa* have also displayed *in vitro* and *in vivo* anti-inflammatory activities: platinum nanoparticles were found to inhibit the expression of pro-inflammatory IL-6 and TNF-α in RAW 264.7 macrophage cell lines (Nematullah et al., 2022), and selenium nanoparticles derived from *C. sativa* seed extract reduced inflammation in a hind paw edema model in female Balb/C mice (Mehta et al., 2021).

Cannabis-derived nanoparticles may also exhibit other biological activities, such as antioxidant and anticancer properties. A

comprehensive summary of these studies is presented in Table 3. Although hemp-derived nanofibers and nanoemulsions appear more attractive for applications in food technology, nanoparticles also hold promise in this field. For instance, Majidiyan et al. investigated the synthesis of industrial hemp essential oil (IHEO) fortified with whey protein nanofibers and mung bean protein nanoparticles (WPNF-MBP NPs) and examined their potential to extend the shelf life of rainbow trout fillets. Fourier-transform infrared spectroscopy (FTIR), showed that applying these nanoparticles to fish fillets effectively inhibited the growth of psychrotrophic and other live bacteria. The study also observed delayed increases in PV (peroxide value), TBA (thiobarbituric acid), and TVB-N (total volatile basic nitrogen) levels during storage. The findings concluded that WPNF-MBP NPs, as a natural preservative, significantly extend shelf life (Majidiyan et al., 2022).

5. Nanoemulsion and nanocapsules

5.1. Nanoemulsions as eco-friendly insecticides

Insecticides based on *Cannabis sativa* oils are an innovative solution for organic crop protection. Essential oils extracted from *Cannabis sativa* are able to repel and kill certain insect species. These products are increasingly being used in organic farming because they are biodegradable and leave no harmful residues. They can also promote soil regeneration thanks to their natural antibacterial properties. Mazzara et al. encapsulated essential oil derived from *Cannabis sativa* (variety "Kompolti") into a nanoemulsion, which proved effective in killing *Culex quinquefasciatus* mosquito larvae (LC₅₀ = 72.2 ppm and LC₉₀ = 207.2 ppm). The nanoemulsion also reduced mosquito fertility. Importantly, it was non-toxic to the aquatic microcrustacean *Daphnia magna*: the mortality rate at the LC₉₀ dose for mosquito larvae was estimated at less than 16 % after 48 hours of incubation (Mazzara et al., 2023). Similar results were reported by Rossi et al., who tested the nanoemulsion on the larvae and pupae of *Anopheles stephensi* and *Anopheles gambiae*. Furthermore, MTT assays revealed that the essential oil was non-toxic to the HaCaT human keratinocyte cell line and NHF A12 fibroblast line, in which it inhibited etoposide-induced inflammatory pathways (Rossi et al., 2020). These studies suggest that nanoencapsulation and nanoemulsion technologies for cannabis essential oil can be effective in producing environmentally-friendly insecticides. It is worth noting that the essential oil used in these studies was extracted from *Cannabis sativa* inflorescences, which are industrial by products of hemp production.

5.2. Nanoemulsion and/or nanoencapsulation technologies in food technology and medicine

Both nanoemulsions and nanocapsules rely on hemp oil: a valuable resource rich in secondary metabolites. Nanoemulsions produced from

Table 4

Application of *Cannabis sativa* (L.) extract with nanoemulsion/nanocapsules in food technology and medicine.

Source/ Extract	Nanoparticles/microcapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
<i>Cannabis sativa</i> L. extract and Aesculus hippocastanum L. extract (AHE)	Nanoemulsion series systems with different concentrations of hemp seed oil (HSO) stabilized with AHE- A. hippocastanum L. extract	The highest stability-emulsion with 5 % HSO and 2 g/L AHE in water	-	-	Anti-inflammatory properties, combination of AHE with HA and hemp seed oil in emulsion systems- increased nutritional benefits Decreased significantly the formation of edema and granulomatous tissue, attenuated significantly the recruitment of inflammatory cells in the tests for peritonitis and leukocyte infiltrated, the histopathology analysis of the gastrocnemius muscle confirmed a reduction in tissue damage, anti-inflammatory activity	Jarzębski et al., (2021)
<i>Cannabis sativa</i> -fixed oil CSO	Nano-emulsion with herbal derivative (NCS) against VBm (toxin from Bothrops moojeni snake venom)-induced inflammation	CSO concentration 200 and 400 mg/kg and NCS- 100 mg/kg	-	<i>In vivo</i> - in male Wistar rats	Nutritional application- ideal source of omega-3 fatty acids, vegetarian product, antioxidant activity, an ideal ratio of omega-3 and omega-6 fatty acids 1:3	de Oliveira Carvalho et al. (2021)
<i>Cannabis sativa</i> -hemp seed oil	Nanoemulsification of hemp seed oil	-	-	-	Lower levels of pro-inflammatory cytokines compared to the positive control, safety biology profile of hemp EOs and their NEs	Amiri-Rigi et al., (2023)
<i>Cannabis sativa</i> - (hemp essential oil (EO) from different cultivars Carmagnola CS and Uso 31)	Encapsulated form (nanoemulsion, NE)	Containing the 5 % and 6 % w/w of EOs	-	human keratinocytes, fibroblasts and bronchial epithelial cells: HaCaT, NHF A12HBEPc	Protected rats against NASH progression, decreased the percent of BWt (body weight change), protective activity against insulin resistance (IR) and hepatic pathology	Aguzzi et al., (2023)
<i>Cannabis sativa</i> -Hemp seed oil	Nanoemulsion preparations of hemp seed oil	Hemp Seed Oil 40 % (v/v)	-	<i>In vivo</i> - Adult male Wistar rats +Non-alcoholic steatohepatitis (NASH)-metabolic liver disease	The nanoemulsion system- stable and safe formulation, potential biological activity, health benefits, potentially using in the food industry	Qushawy et al., (2022)
<i>Cannabis sativa</i>	Formulation of nanoemulsion contained hemp seed oil and the A. hippocastanum L. extract (AHE)	0.25 mL of the emulsion	Lactobacillus sp.	-	Emulsions with extract of Saponaria officinalis exhibited toxic activity (the cell metabolic activity reduced to 80 %), in contrast to Quillaja emulsion-induced P. fluorescens ATCC 17400 growth	Smulek et al., (2021)
<i>Cannabis sativa</i> - oil-in-water (Oil/Water) emulsion based on HSO-hemp seed oil	Nanoemulsion System	Critical micelle concentration CMC in the range 0-2 g/L	<i>P. fluorescens</i>	-	Smaller droplet sizes	Jarzębski et al., (2020)
<i>Cannabis sativa</i> extract with emulsion powders- CS-PA/MD	Hemp seed oil-in-water Pickering nanoemulsions	-	-	-	Quillaja emulsion-induced P. fluorescens ATCC 17400 growth	Tabatabaei et al., (2022)
Industrial hemp (<i>Cannabis sativa</i> L.)	Nanoparticles- complexing hemp globulin (HG) with sodium caseinate (SC)	Composed of 30 % water phase and 70 % oil phase (v/v), contained 2 % protein (w/v, pure SC/HG-SC nanoparticles with	-	-	Exhibited toxic activity (the cell metabolic activity reduced to 80 %), in contrast to Quillaja emulsion-induced P. fluorescens ATCC 17400 growth	Chuang et al., (2020)

(continued on next page)

Table 4 (continued)

Source/ Extract	Nanoparticles/microcapsules	Concentration/ Volume/IC50	Strain MIC/ microorganism/ parasite	Cell line/ in vivo	Effect	Ref.
<i>Cannabis sativa</i>	Nanoemulsions, based on hempseed oil (HSO)	an HG: SC ratio of 1: 2/ 1: 1 Moderate concentration (4–8 wt%)	-	Caco2-cell model,	Stability for oral delivery applications, a proper morphology examination, - proper simulated release behavior test in the gastrointestinal tract- evaluating trans- membrane transport - toxicity study	Fathordoobady et al., (2021)
<i>Cannabis sativa L.</i>	Nanoemulsion (NE) with two active components in cannabis extracts (THC) and Cannabidiol (CBD)	0.7 mL containing 21 µg of the mixture of THC and CBD per injection	-	<i>In vivo</i> -Animal model (C6 tumor model) in rats of glioblastoma- the Wistar rats	Successfully decreasing brain glioma tumor progression, NED drug delivery - hemocompatibility (RBC, MCHC, RDW, MCV, MCH, PPP, PT and PTT) increased	Mobaleghol Eslam et al. (2024)
<i>Cannabis sativa L.</i>	Phytocannabinoid nanoemulsion	16.6 wt% CBD- enriched cannabis distillate (emulsion containing)	-	-	Robust and stable systems even at low emulsifier concentrations	Banerjee et al., (2021)
<i>Cannabis sativa L.</i>	CBD nanoemulsion system using (MCT), canola oil (CO) and hemp seed oil (HSO)	-	-	-	Improved bioavailability of CBD compared to that of bulk oil forms in all three nanoemulsion formulations	Zheng et al., (2022)
<i>Cannabis sativa L.</i>	Nanoemulsions (NEs) with hemp oil and less surfactants	Concentration 10 µg/mL	-	SpragueDawley rats following oral administration, Caco–2 cells	Ameliorating the oral bioavailability of BCL (baicalein), excellent intestinal permeability, good transcellular transport ability and low cytotoxicity- acceptable for oral purpose	Yin et al., (2017)

hemp oil not only exhibit a range of biological activities (e.g., anti-cancer, antibacterial, anti-inflammatory, hepatoprotective, and anti-insulin resistance effects) but also enhance the bioavailability of both cannabis-derived metabolites (e.g., CBD) and those from other plants (e.g., baicalein). Studies confirming these effects are summarized in Table 4.

Hadidi et al. utilized nanocapsulation technology to encapsulate hemp essential oil (HBEO) in alfalfa protein nanoparticles, significantly improving the thermal stability of the essential oil and enhancing its antioxidant activity compared to free HBEO (Hadidi et al., 2022). Similarly, Lajoie et al. demonstrated that using emulsifiers (whey protein isolate, soy protein isolate, and Tween 80) during the nanocapsulation process of hemp oil with maltodextrin via spray drying improved the bioavailability of cannabinoids (THC, CBD, CBN) in an *in vitro* digestion model. Among the tested emulsifiers, Tween 80 yielded the best results (Lajoie et al., 2022). These findings suggest that both nanoemulsion technology and nanocapsulation processes can effectively enhance the beneficial properties of *C. sativa*-derived resources, particularly hemp oil and essential oil. Such technologies hold promise for applications in both medical fields and the production of functional foods. A schematic representation of the combination of hemp potential and nanoparticles is presented in Fig. 2.

6. Conclusions and future perspectives

Cannabis sativa has historically been used by different cultures around the world for both practical and ritual purposes. Cannabis was one of the earliest cultivated plants and its uses included textiles,

medicine, rituals, food and military purposes. Today, the plant is widely used in fibre production, construction, the food industry, medicine, cosmetics, the energy industry, the chemical industry, agriculture and paper production.

The ethical and medical aspects of *Cannabis sativa* use, and providing equal access to cannabis-based medicines, remain the subject of much debate. Nevertheless, its use in therapy requires particular attention to ensure adequate dosage control and minimise the risk of abuse. It is also important to ensure that research on *Cannabis sativa* is conducted in a transparent and independent manner, taking into account the public interest. Nevertheless during the commercialisation of cannabis, the traditional knowledge of indigenous peoples, who have used cannabis for medicinal purposes for centuries, should be protected from unfair appropriation.

The intensive development of modern technologies makes it possible to predict further optimization of the ecological synthesis of *Cannabis sativa* nanostructures. This will play a key role in scaling up processes while maintaining sustainable development and reducing energy consumption. The range of medical applications related to the production of advanced hemp-based nanomaterials may well expand to include personalised medicine, targeted drug delivery and the development of biosensors for real-time diagnostics. Regenerative medicine and tissue engineering may also be included in such applications. Hemp-derived components should be further explored for their applications in supercapacitors and batteries. Interdisciplinary research combining Botany, Materials Science and Nanotechnology is the best approach to unlocking the innovative potential of *C. sativa*. Its combination with nanotechnologies will be an important step towards identifying sustainable

Cannabis sativa with nanoparticles

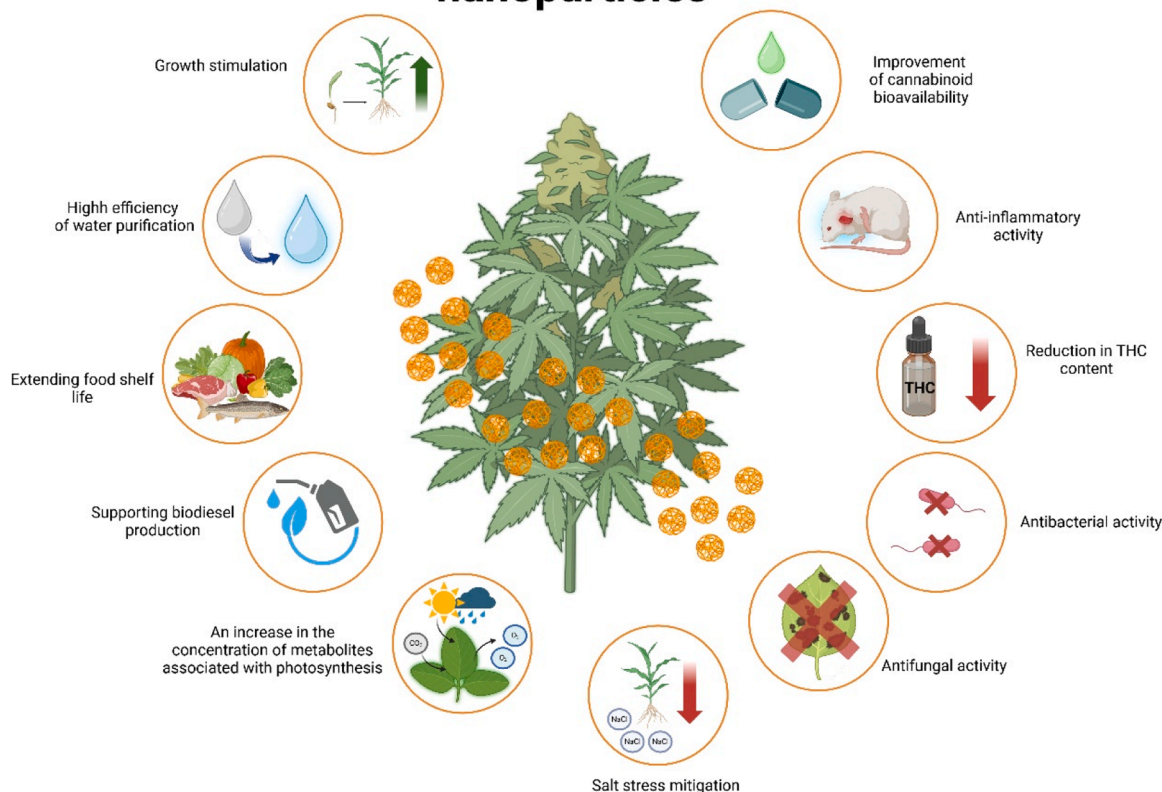


Fig. 2. Use of *Cannabis sativa* (L.) products in combination with nanoparticles (Created with BioRender.com).

industrial solutions that will address global challenges in health, agriculture and environmental protection.

CRedit authorship contribution statement

Sitarek Przemysław: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Hatziantoniou Sophia:** Writing – review & editing, Investigation. **Muskala Martyna:** Resources, Investigation. **Glica Magdalena:** Resources, Investigation. **Mori Matia:** Writing – review & editing, Investigation. **Picot Laurent:** Writing – review & editing, Investigation. **Górski Karol:** Writing – review & editing, Visualization, Investigation. **Gładys Aleksandra:** Resources, Investigation. **Kowalczyk Tomasz:** Writing – original draft, Visualization, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

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No data was used for the research described in the article.

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