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Case Report

Knowledge mapping for a secure and sustainable hemp industry: A systematic literature review

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ABSTRACT

As a versatile and multipurpose plant, hemp (*Cannabis sativa* L.) possesses immense potential for its application in nutraceuticals, food and nutrition, fibre, and construction material. However, its broader industrial potentials are hindered by the lack of sufficient knowledge on varietal differences, phytochemical properties, food and fibre processing techniques, bioenergy application and valorisation of whole plant, clinical evidence, and standardised quality control mechanisms. In this context, we systematically reviewed 101 reviews and 655 research papers on hemp to map what we already know and what we still need to know about hemp, across its supply chain; from cultivar selection through production to end use. We reviewed the literature based on major themes and sub-themes. Existing literature spanned 33 sub-themes of hemp, which can be classified under five broad themes: production, material, health, futures, and research and education. The 'material' theme (42%) was the most researched, followed by 'production' (27%) and 'health' (19%). At the sub-theme level, one-fifth of the research articles covered fibre and composite material (n = 139), followed by phytochemical analysis and potency testing (n = 45), hempcrete and construction applications (n = 43), and germination and plantation techniques (n = 41). More than half of the selected research articles on hemp were published in the last three years (2020–2022), concentrated mainly in North America, Europe, and China. Cannabidiol, fibre, and seed oil were considered as the quick wins of hemp industry (hemp champions). Based on our review, we have discussed various research gaps and research priorities across the supply chain, beginning from early detection of hemp breed to valorisation of hemp hurd and industrial residue to address opportunities and challenges for the industrial development of major hemp products.

1. Introduction

Hemp has been attracting growing attention in agro-industrial research and development sectors, not because of its psychoactive potential, but rather for its immense agronomical and industrial opportunities in global markets [1–3]. Distinguished from marijuana by its lower delta-9-tetrahydrocannabinol (THC) content (<0.3% in North America, <0.2% in Europe), industrial hemp (*Cannabis sativa* L.) has been considered an extremely versatile commodity with a wide range of potential applications across environmental protection, food and nutrition, paper and textile industry, composite material, green energy and infrastructure, and nutraceutical use [1,3–5]. Out of 545 phytochemicals reported in hemp [6], Cannabidiol (CBD) is one of the non-psychoactive components of hemp which indirectly influences the human endocannabinoid system to regulate multiple physiological processes and maintain homeostasis [7–10]. Similarly, eco-friendly production and multipurpose application of hemp fibre makes hemp a superior natural fibre product [11,12]. In addition, the nutritional and nutraceutical values of seed oil and seed cake have positioned hemp as a superfood in functional food industries [4,13,14]. However, the future of hemp depends on the research and development on its genetics, phenotypic plasticity, agronomic feasibility, and the scalability of the industry.

Although hemp has a long history of cultivation and use, especially

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for fibre during colonial trade expansion, it was banned in most parts of the world in the early 20th century. Different countries have their own history of its use, yet the global importance of hemp was revitalized when the USA distinguished hemp from marijuana in 1970, Canada allowed the production of hemp (<0.3% THC) from 1996, the USA allowed hemp for research in 2014 and for food supply chain in 2018 [15]. Currently, over 47 countries grow hemp for research and/or commercial purposes [4], and about 25,000 hemp-based products exist in the global market [16]. Countries have different regulatory models for legalizing hemp, for example, 36 countries have already put the regulatory model in place for legalization of hemp and it is under development in 20 other countries [17]. More details about recent advancement and legalization of hemp, along with the global map of the countries with their legal status for hemp, can be found in a paper by de Souza et al. [17]. The scope of the hemp industry is ever-increasing in terms of its agronomical suitability, environmental benefits, and economic potential. The global hemp market is expanding and it is expected to increase by about 250% by end of 2024 compared to US$ 17.7 billion in 2019 [18]. However, the sustainability of hemp industry might depend on identification of target products which provide early wins and easy rewards, technological improvement in production and processing, and ensuring efficient and transparent supply chains.

While acknowledging the potential of hemp industries, high levels of uncertainty and low levels of confidence remain among market stakeholders [19,20]. In addition, legislative unclarity, legacy narratives and disparate political views, combined with complexities in monitoring chemical constituents (mainly, CBD and THC), value addition, and supply chain competition further challenge the sustainable hemp industry. To tackle the regulatory challenges, as well as other agronomic and economic challenges, rigorous research and development is needed to enable evidence-based decision making. However, due to a rise in the product demand, hemp industries are growing without adequate research support [21]. As a result, the hemp industry is suffering from a lack of suitable varieties for different environments and end uses, inefficient agronomic practices, bottlenecks in processing and manufacturing, inconsistent product performance, unrealistic labelling, and a lack of adequate standards [22–25].

While interest in hemp research is increasing, an inventory across the research landscape of hemp is missing. Although a range of reviews exist for cannabis [17,20,26,27], they had a sectoral focused. For example, a bibliometric analysis done by Liu et al. [27] was primarily limited to CBD and claimed that cannabis research was dominated by pharmacology, chemistry, and molecular biology, while a review by Gomez et al. [20] focussed on cannabis as a feedstock for fuels, chemical and materials across the topics of agriculture, engineering, biochemistry. Similarly, Crini et al. [26] reviewed the uses and applications of hemp and de Souza et al. [17] reviewed the regulatory framework of hemp. Yet, there is a lack of comprehensive review of various other aspects of the hemp industry, such as genetics and cultivar selection, plant propagation and germination, cultivation and crop management, post-harvesting and processing, manufacturing and value addition, and market scoping of hemp. Similarly, as a multipurpose crop, hemp can be used for its various parts and products. However, hemp 'champions' which denote the hemp products which have high potentials of quick wins and easy rewards to the hemp industry, have not been identified and discussed thus far. Analysis of global publication trends and documentation of the findings of research and review articles, which can help distil research priorities as well as highlight the best performance trajectory of hemp, is missing.

In this paper, we carried out a multistage review (i.e., review of the review articles followed by the review of research articles) of hemp, to map out the findings of previous studies on hemp and identify research gaps. The novelty of the paper is the use of two-stage systematic review of articles on hemp to map the research knowledge across the hemp value chain, such as outlining what has been known and what is yet to know to foster sustainable hemp industry. A review of the review articles identified key research themes and sub-themes throughout the whole hemp supply chain, while the review of research articles outlined publication trends, coverage, nature, and types as well as to document the knowledge base under each identified theme/sub-theme. All articles were considered to identify potential hemp champions, find knowledge gaps, and recommend future research trajectories. Our review is different from the previous hemp reviews because we aimed to carry out a systematic review of literature, stretching throughout the supply chain of hemp, which might help to overcome the deficiencies of conventional sectoral reviews against the broader research landscape.

2. Methods

We adopted a systematic literature review (SLR) approach for this study, including both quantitative bibliographical analysis as well as qualitative content analysis. SLR was carried out to overcome potential biases and to enhance transparency and replicability of the research, which is crucial in documenting and valuing what was done, found and reported in previous research [28–30]. We followed a structured methods of formulating the research questions, setting review protocol, database selection and literature search, article screening and selection, data extraction and analysis [28,31]. Along with the identification of our research aim of mapping available knowledge for the sustainable hemp industry, we selected keywords for the literature search balancing the sensitivity and specificity in determining the number of articles for review. We remained inclusive of all aspects of the hemp industry by setting the keywords as 'industrial hemp'. Accordingly, the search string of the SLR was '(Industr* OR commercial*) AND (Hemp OR "Cannabis sativa") which was used to find the articles in two comprehensive bibliographic databases: Web of Science Core Collection and Scopus. A methodological flowchart of SLR is presented in Fig. 1.

The literature search was carried out in April 2023. For the review articles, we selected the articles which were published on and after 2020 to ensure the review of recently published review articles and to refrain from the old reviews which might have already been addressed in the recent literature. In case of research articles, all the papers which were published until 2022 were included in this review, without any restriction on year of publication, aiming to include all research findings about hemp throughout the historical time frame. We found a total of 322 records of review articles and 3755 research articles in both databases, which contained the unique records of 226 and 2537 articles, respectively, after the removal of duplicates.

Article screening was done in two phases. First, title and abstract screening were done by removing all the articles which did not contain hemp or cannabis in the title. Papers with generic information and essays about history, occurrence, and importance which were not explicit about genetics, agronomy, or economy of the hemp in the title or in the abstract were removed. All theoretical papers, perspective and commentary papers, discussion papers, and reports were excluded during the title and abstract screening. Besides, the papers which did not consider hemp as a primary plant species during review and research were also excluded. During the screening, 51% and 71% of review and research papers were excluded, respectively, leaving 111 review papers and 788 research papers for further screening. Secondly, full-text screening was done based on the pre-defined selection protocol (Fig. 1). For the review papers, all the articles which did not contain the inclusion protocols mentioned in the title and abstract screening, articles not in English, articles based on empirical research, and general reviews without any conclusion and/or findings were removed. In the case of research articles, we employed the elements of Population-Intervention-Outcome (PIO) elements for the selection. Accordingly, all the articles which did not contain population (i.e., hemp or cannabis), intervention (i.e., observation or testing and experimentation or cultivation or processing and manufacturing or modelling and simulation or survey and evaluation or analysis), and outcome (i.e., characterization or effect in any life cycle component of hemp) were removed from full-text research

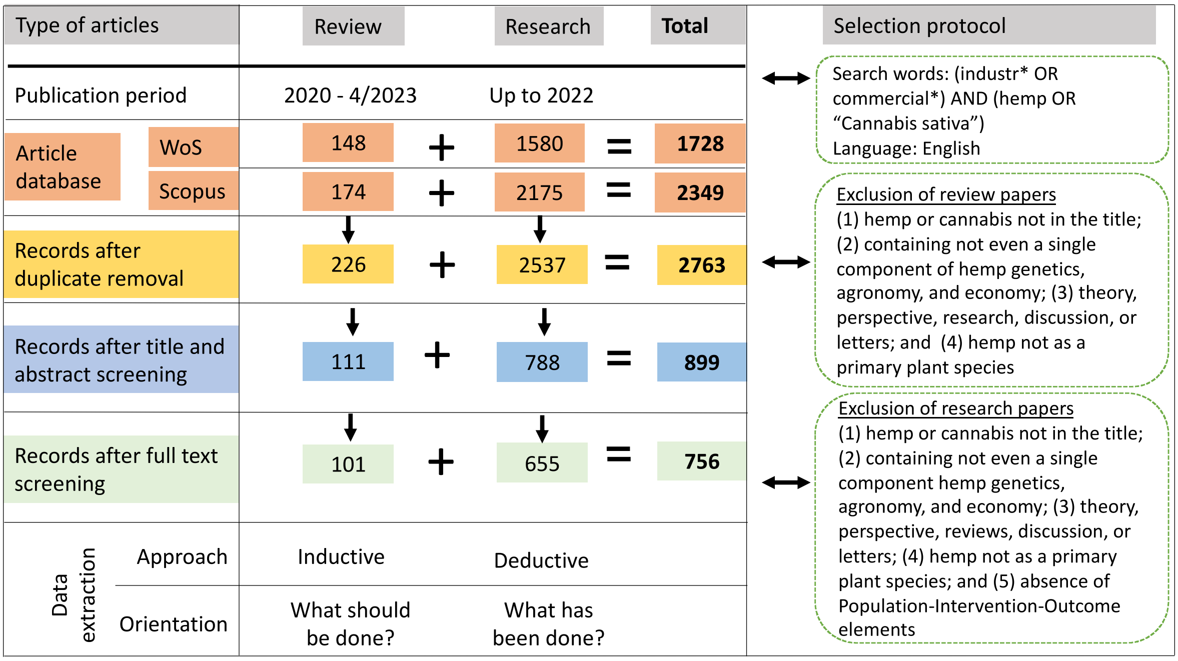

Fig. 1. Methodological flowchart showing the papers selection processes, including the description of search string and inclusion and exclusion criteria.

articles screening. Finally, 101 review articles and 655 research articles, 756 altogether, were considered for data extraction. Details of the selected articles are presented in **Supplementary File 1**.

Data extraction for review articles was done through an inductive approach, which identified major themes and sub-themes of the research based on the observations and findings in previously published papers. Basically, we examined the patterns, trends, and themes of the review papers. We focused on key contents, major arguments, key findings, and conclusions of the review papers. Based on the topic, contents, and findings of the review articles, we grouped and characterized different dimensions (i.e., themes and sub-themes) of research on industrial hemp. The SLR of the review articles depicted a total of 33 dimensions (i.e., sub-themes) of research in the hemp industry, which were grouped into five major themes (Table 1).

Based on the identified research dimensions (sub-themes), we followed the deductive approach in the SLR of research articles to map out the available knowledge base, identify relevant literature in each sub-theme, evaluating and summarizing research findings. After data extraction, the data analysis was done through comparative analysis and argumentative discussion of the findings from both review and research articles. The details of the findings from each of the reviewed articles is presented in **Supplementary File 2**.

Table 1
Themes and sub-themes of research about industrial hemp.

Themes	Sub-themes **of hemp research**
Production	(i) genomics, (ii) cultivars, (iii) disease and pests, (iv) germination and plantation techniques, (v) harvesting time and techniques, (vi) photoperiod, (vii) fertilization, and (viii) climatic factors
Material	(i) post harvesting operations and drying, (ii) bioactive compound extraction and processing, (iii) fibre extraction, processing, and treatment, (iv) seed oil extraction and storage, (v) paper and textile, (vi) composite materials, (vii) hempcrete and construction applications, and (viii) bioenergy
Health	(i) phytochemical analysis and testing, (ii) clinical trials, (iii) quality control, (iv) patent and intellectual property rights, (v) medicinal applications, (vi) food ingredients, (vii) animal feed, and (viii) workers' health and safety
Futures	(i) environmental sustainability and challenges, (ii) carbon sequestration and storage, (iii) phytoremediation potentials, (iv) market value and potentials, and (v) policy and regulations
Research and Education	(i) coordination and collaboration, (ii) database management and modelling, (iii) scientific research and publications, and (iv) stakeholders' perception and interest

3. Results

3.1. Temporal and geographical distribution of research articles

A total of 665 published research articles met our inclusion criteria, out of which only four articles were published before 1990 (Fig. 2). A clear positive trend of publication was observed since 2013 with a one-year dip in 2016. More than half of the total papers (>53%) were published between 2020 and 2022 and the publication of research articles nearly doubled between 2021 (n = 91) and 2022 (n = 178).

A total of 58 countries were involved in publishing research articles about industrial hemp (Fig. 3). Top research countries were the USA (n = 108), Italy (n = 99), Canada (n = 48), China (n = 42), France (n = 36), Poland (n = 36), and Australia (n = 23). Although most of the countries focused on whole plants for multipurpose applications of hemp, different countries have shown different priorities of research. For example, 37% of the research papers from USA focused on bioactive compounds while over 60% of the research papers from France focused on fibre as the main parts of hemp plant. Similarly, over 30% of the articles from USA and Australia focused on medicinal applications of hemp while France has focused on composite material (>30%) and hempcrete (>22%) as the products of interests from hemp. The details of research articles, including the focus on research based on parts of plants, product of interest, research themes, and subthemes from the countries with higher number of research publication (i.e., >20 research articles) is presented in **Supplementary File 3**.

3.2. Research articles' category and journal

Industrial hemp was found to be covered by broader categories and/or subject areas of publication (Table 2). As per the Scopus database, most of the research articles were published under the category of agricultural and biological science (33%), followed by material science,

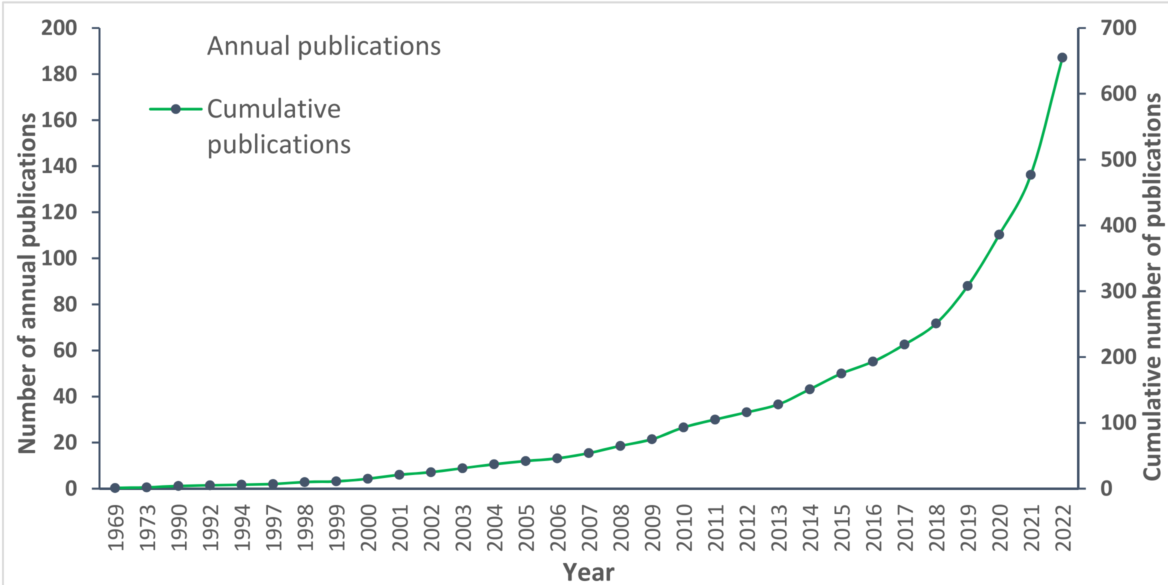

Fig. 2. Number of research articles published year by year and cumulatively.

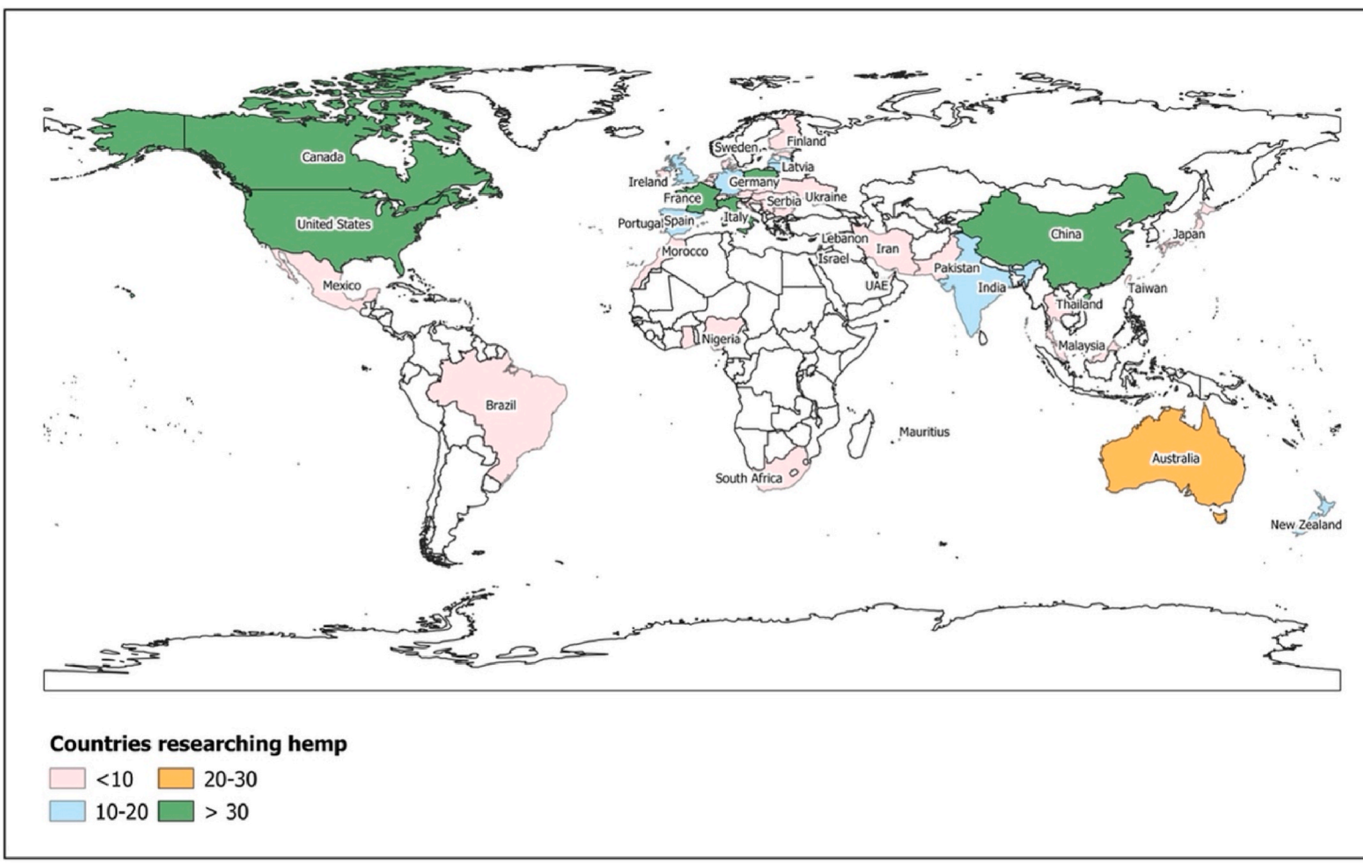

Fig. 3. Countries showing the frequency of research publication by the leading author's institutions.

engineering, environmental science, and chemistry. Likewise, the Web of Science category of publications showed that most of the hemp research fell under the category of agronomy (13%), agricultural engineering, plant science, or material science. Some of the articles were categorized under various disciplines such as energy, pharmacology, medicine, microbiology, and even computer science.

Interestingly, 301 journals were involved in the publication of 655 research articles (Fig. 4); however, only 22 of them published over five research articles. Industrial Crops and Products remained the highest publishing journals in hemp (n = 81) followed by Journal of Natural Fibers (n = 23), and Molecules (n = 16). A couple of journals were found to be focused on hemp namely, the Journal of Industrial Hemp and the Journal of Cannabis Research, producing 11 and 9 research articles, respectively, that are included in our SLR. Various journals of multi-

Table 2
Percentage of research articles according to top 15 category/subject area[a].

Categories based on Scopus	%	Categories based on Web of Science	%
Agricultural and Biological Sciences	33	Agronomy	13
Materials Science	28	Agricultural Engineering	11
Engineering	21	Plant Sciences	9
Environmental Science	17	Material Science Multidisciplinary	8
Chemistry	16	Food Science Technology	8
Chemical Engineering	14	Polymer Science	7
Biochemistry, Genetics and Molecular Biology	11	Environmental Sciences	7
Medicine	9	Chemistry Multidisciplinary	6
Energy	8	Energy Fuels	6
Business, Management and Accounting	7	Biotechnology Applied Microbiology	5
Pharmacology, Toxicology and Pharmaceutics	7	Material Science Textiles	5
Social Sciences	5	Material Science Composites	5
Physics and Astronomy	4	Biochemistry Molecular Biology	5
Immunology and Microbiology	3	Chemistry Applied	4
Computer Science	2	Engineering Chemical	4

[a] Note: this proportion was based on the number of research articles before screening and selection.

disciplinary streams have also published hemp research, such as Bioresource Technology, Materials, Biomass and Bioenergy, Food Chemistry, and Polymers.

3.3. Priority parts of hemp and products of interest

More than one-third of the selected articles focused on the whole plant, rather than separate single parts of the plant (Fig. 5). Fibre was the priority plant part as mentioned by 28% (n = 183) of the research articles. A substantial proportion (19%; n = 121) of the selected research articles focused only on bioactive compounds (mainly cannabinoids, including terpenes and flavonoids). Hemp seeds were focused by 10% (n = 66), while 6% (b = 42) articles focused on the use of hemp residues. About 33% (n = 217) of the articles claimed hemp for multipurpose application, followed by its priority in medicinal application (21%; n = 135), composite materials (12%; n = 78), food ingredients (10%; n = 66), hempcrete (7%; n = 46), and others. Nevertheless, majority of the articles admitted consideration of multiple parts of the plants and proliferation of multiple use of hemp as an ideal approach for growing hemp industry.

3.4. Research themes and sub-themes of industrial hemp

Out of the total 33 sub-themes identified while reviewing review articles, 30 of them were depicted in the SLR of research articles. Proportion of research articles under each theme, and further under each sub-themes is presented in Fig. 6.

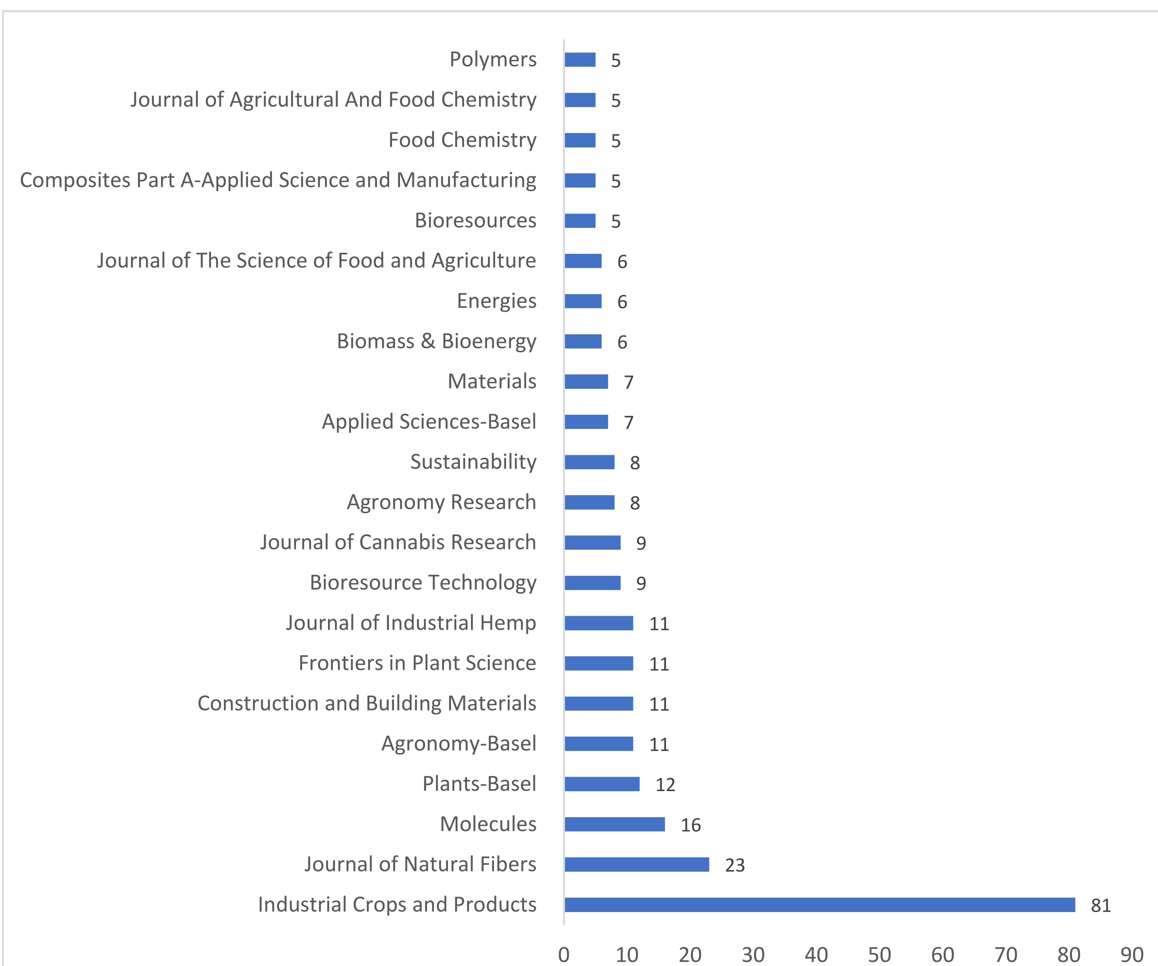

Fig. 4. Journals with high frequency of publication of the research articles.

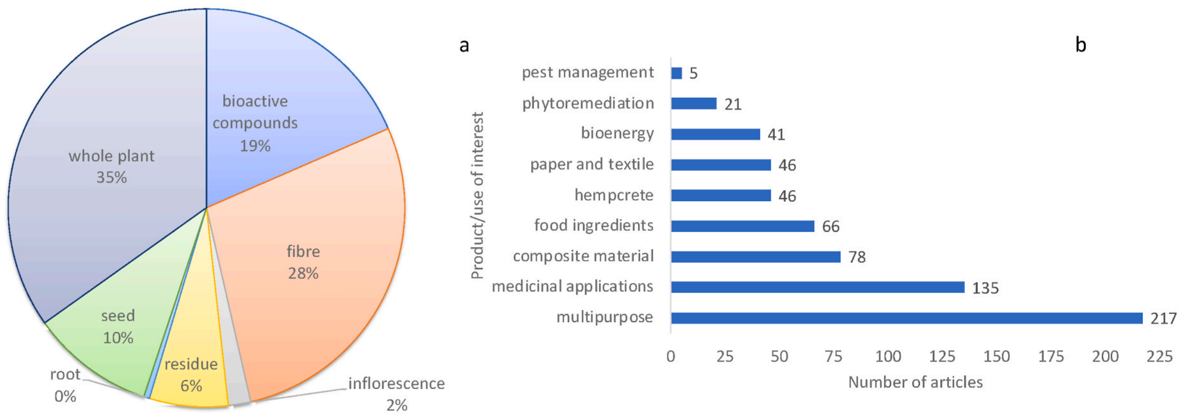

Fig. 5. Plant parts and products of hemp: priority part of the plant (a) and product of interest or end use (b).

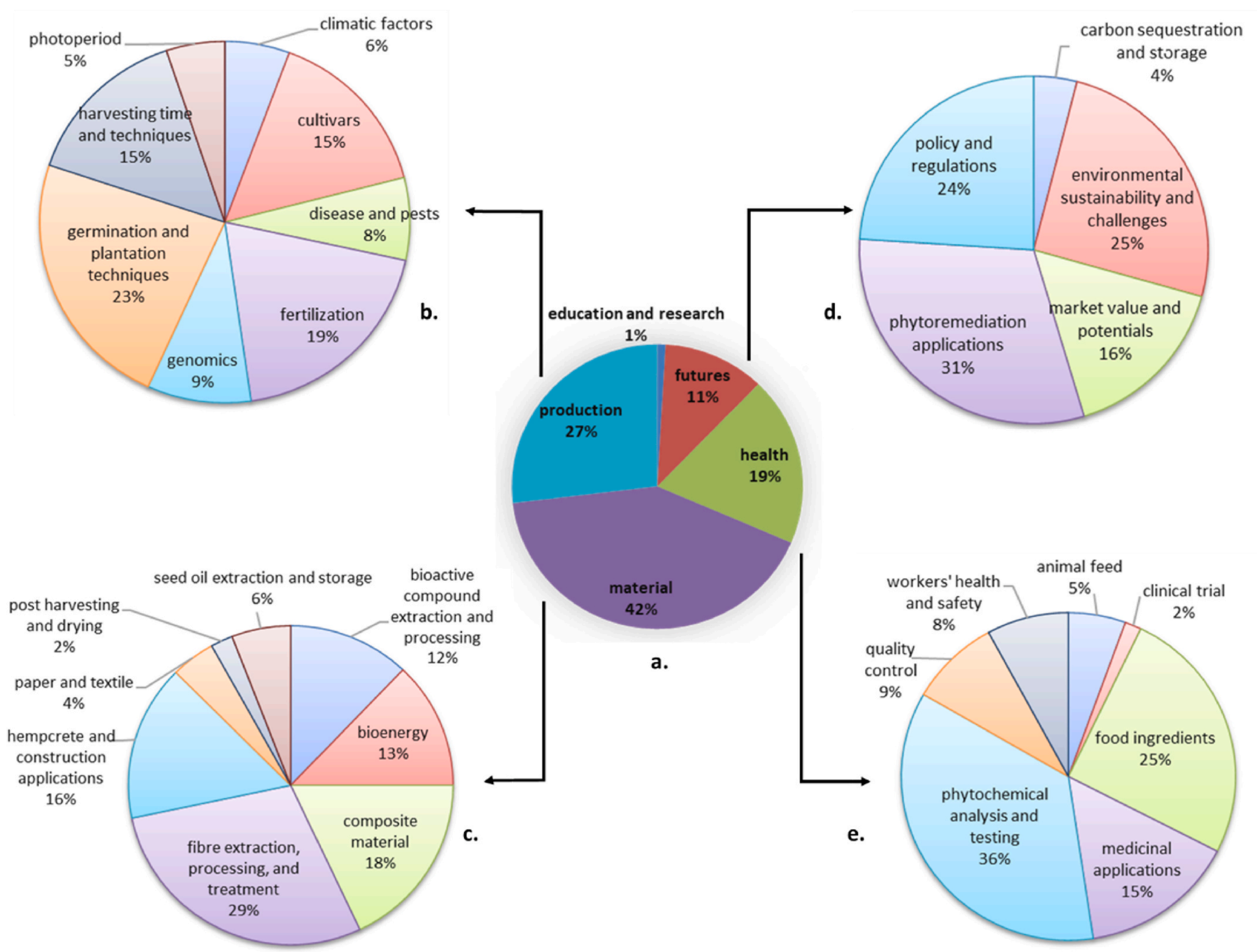

Fig. 6. Themes and sub-themes of the research articles. Pie chart at the centre (a) denotes percentage of articles under five major themes, other four charts at the corners show the percentage of articles with various sub-themes under each of the major themes of (b) Production, (c) Material, (d) Futures, and (e) Health. Note: only six research articles were depicted under Education and research: five about 'stakeholders' perception and interest', and one about 'database management and modelling'.

The highest number of articles (42%) were published under the major theme of Material, followed by Production (27%), Health (19%), and Futures (11%). Only six articles were related to Education and Research. Under the production theme (Fig. 6b), the highest number of publications were about germination and plantation techniques (23%), followed by fertilization (19%), harvesting time and techniques and cultivars, each accounting for 15%. Research articles under the material theme (Fig. 6c) were dominated by fibre extraction, processing, and treatment (29%), which was followed by composite material (18%) and hempcrete (16%). Only two percent of the research articles primarily dealt with post-harvesting and drying while 4% were focused on paper and textile application of industrial hemp. More than one-third of the publications under the health theme (Fig. 6e) were focused on phytochemical analysis and potency testing, followed by food ingredients (25%) and medicinal applications (15%). Research articles about phytoremediation through hemp cultivation dominated the themes of the futures (31%), followed by environmental sustainability as well as challenges (25%) and policy and regulations (24%). Only a handful number of articles (4%) focused on carbon storage and sequestration potentials of hemp under the theme of the futures.

3.5. Characteristics of research and knowledge base

3.5.1. Production theme

High number of studies were about germination and plantation techniques, nitrogen fertilization, genomics, and cultivar selection for hemp production. For example, *in-vitro* propagation of hemp [32,33], seed treatment [34,35], effect of irrigation on biomass production and chemical constituents [36,37], as well as sowing density and sowing season [38,39] have been studied in various parts of the world. The benefits of rotational cropping [40], maintenance of seed viability for up to six months [41], optimum temperature for photosynthesis [42], and self-walking hemp seeder were among the other research topics in germination and plantation of hemp [43]. Studies on fertilization in hemp are dominated by nitrogen fertilization, with a common understanding of its application for biomass increment up to the application rate of 150 kg/ha [44–46]. However, some studies suggest that fertilization can increase CBD and THC at rates up to 60 kg/ha [47] while others do not support any correlation of yield with CBD and THC content [48–51]. Yet, some studies have suggested alternatives to nitrogen fertilization through the inoculum of rhizobacteria [52], biogas digestate [53], humic acid [54], silkworm manure [55], and vermicompost [56].

Similarly, genetic and functional genomic studies have led to rapid identification and characterization of genes underpinning key fibre traits [57], differentiating male and female plants [58,59], the effect of genotype on chemical constituents of end-products [60], genetic transformation [22], differential gene expression affecting fibre biosynthesis [61], and molecular markers to distinguish key chemotypes [62]. Few studies have discussed detection and analysis of hemp and drug type [63], while single nucleotide polymorphism assays have been reported to discriminate hemp types even before the accumulation of cannabinoids [64]. Different cultivars were studied and recommended for different purposes in the literature, the most popular being Futura 71 for the highest green biomass and CBD content [65,66], Fedora 17 for seed and vegetable oil [67,68] and Bialobrzeskie and Beniko for fibre production [69–71]. Yet, there was no consensus among the studies (see Annex 1). Research on photoperiod included speed breeding [72], effects of light quality (i.e., white and blue) [73], photoperiod sensitivity [74,75], and recommendation of optimum photoperiod [76]. Effect of harvesting time on fibre properties, biomass yield, and chemical constituents has been investigated in detail, for example, the suitability of early harvesting for high quality primary fibres [77–80], and bud stage harvesting for good CBD:THC ratio [81]. Drought tolerance properties of hemp [82,83], the effect of drought stress on CBD content [84], as well as topographical and latitudinal aspects of hemp have also been discussed [85,86]. Besides, potential pests in hemp such as aphid species [87], Pythium and Fusarium species [88], and powdery mildew pathogens were discussed [89,90], and potential biological control have been proposed [91].

3.5.2. Material theme

Under the largest theme, Material, with 42% of articles, studies included post-harvesting operations to processing and manufacturing of hemp products. Research on hemp material starts with examining the importance of stripping leaves and heads for drying purposes [92], novelty in cleaning and separation of hemp biomass [93], mechanical and chemical separation [94,95], and the effectiveness and efficiency of various drying methods [96,97]. Most of the research in bioactive compound extraction was targeted at competitive advantage and comparing different methods for extraction of CBD, supercritical carbon dioxide (SCO_2) extraction being the most common for commercial application, especially for the extraction of CBD [98–100]. Yet, other methods were also discussed in the literature, including but not limited to microwave-assisted extraction [101–104], ultrasound extraction, cold pressing [105], and pressurized hot water extraction [106]. Various studies have also considered the use of solvents (i.e., ethanol) [100,107], solvents free extraction methods [108], osmotic treatment [109], hydrodistillation [110], and the consideration of temperature and pressure during the extraction of bioactive compounds [98,99,104]. Likewise, SCO_2 extraction is considered a promising method for seed oil extraction, followed by Soxhlet, ultrasonication, ultrasonication-treated Soxhlet, and Soxhlet-treated ultrasonication [111]. Seed oil extraction is also studied from the perspective of using solvent to yield superior protein quality [112,113], grading of seeds [114], proper oil storage to minimize oxidation [115], and miniaturization of characterization of seed oil quality [116]. Additionally, there has been a long history of research in fibre extraction, treatment and processing ranging from identification of primary fibre rich plant part [117,118], decortication efficiency [119], comparison of various retting methods (i.e., field retting, water retting, dew retting, controlled retting in the pond and well) [120,121], degumming and delignification (alkali and enzymatic) [122], dominant studies on alkali treatment of hemp fibres [123–125], and fibre storage and preservation [126].

Studies on bioenergy applications of hemp highlighted the potential of the plant as a competent energy crop [127,128] and associated use of bioenhancers, fertilization, and treatment to improve relevant yields [129–131]. Additionally, previous studies also included the conversion rate of seed oil to biodiesel (96.87–97.5%) [132,133] and quality standardization of biodiesel based on its low-pressure cloud point and kinetic viscosity [134]. Additionally, a study by Marrot et al. [135] discussed the carbonization of solid biofuels not only the production of biochar but also for electrical conductivity. The use of hempcrete, especially for non-load bearing building structures, because of its excellent thermal (insulation) and acoustic properties [136,137], carbon sequestration potentials [138], and low environmental impact [139,140] has seen 46 publications over the last 14 years from 2009 to 2022. The addition of different proportion of hemp fibre has been prescribed for different purposes, such as 2–3% for good mechanical properties and replacement for standard sand [141–143], 0.5–1.25% to increase shear strength [144], and 0.25% to improve tensile strength of hempcrete [145]. High numbers of studies included findings and discussion of the use of hemp for paper and textiles as well as other composite material. Use of hemp in the production of tissue and towel [146], good quality office papers [147,148], packaging paper [149], traditional clothes [150], and greater dimensional accuracy as the feedstock for other 3D printing are adequality discussed [151], and it was claimed that hemp can replace cotton in terms of both economic feasibility and ecological consideration [152]. Regarding the application of hemp in composite materials, we found most of the studies focused on its mechanical and insulation properties [153,154], energy and weight-saving applicability [155,156], flexibility to mix with wheat gluten plastics [157], expandable graphite [158], and synthetic epoxy-based samples [159] to improve their quality and performance [160]. Although the proportion of hemp varies according to different studies, most of them recommended up to 30% by weight as the best for versatile application in composites [161–164].

3.5.3. Health theme

Hemp seed has been reported as a superfood because of its fibre content and digestible protein [165–171]. Hemp seed is also well-known for its nutritional mineral content [172–174]. The level of nutritional value however differs, such as hemp protein has highest nutritional values whereas CBD extracts have the lowest one [175]. Similarly, hemp seed oil is well known for its optimum ω-6/ω-3 fatty acid ratio, ranging from 1.71 to 3.6 [176–179]. Studies reported that it has been used in various food items, such as bread [180], pasta [181], high-value beverages [182,183], and bakery items [184,185]. It has also been reportedly used as animal feeds for dairy cattle and lamb to improve their health and meat quality [186–188].

Medicinal application of hemp is characterised by its biologically active metabolites found in different parts of the plants, reportedly having antioxidants, anti-inflammatory, and anti-ageing properties [189,190] as well as it has also been used to treat cancer by reducing oxidative stresses and inhibiting the viability of different cancer cells [191–195]. Studies have also examined the role of hemp in cosmetic applications [196], treatment of wound and skin infections [197], improving HDL cholesterol [198], treating neurodegenerative disorders [199], and also for various applications for ear treatment and cuts [200], some of which have been confirmed through clinical trials [201,202]. Research on hemp also considered workers' health and safety with the concern of potential physical hazards and exposure to psychoactive substances [203], fungi and endotoxin [204,205], actinobacteria and plant pathogen [206], and chronic and respiratory diseases [207–209].

A substantial number of studies focused on phytochemical analysis and potency testing of bioactive compounds, including cannabinoids, terpenes, and flavonoids. There is not a consensus about which analytical method is the best one but literature discussed numerous methods, including: Gas Chromatography-Mass Spectrometry [210–212], high performance liquid chromatography [213], Direct Analysis in Real Time Mass Spectrometry [214,215], quantitative nuclear magnetic resonance spectroscopy [216,217], Near-infrared spectroscopy [218,219], Raman spectrometry [220], liquid chromatography Photodiode Array detection [221] and many others. They have claimed their own strengths, such as liquid chromatography Photodiode Array detection is claimed to give precise results (>92.1% accuracy for all compounds) within 13 minutes [222,223], reverse-phase–high- performance liquid chromatography–-photodiode matrix system is claimed to detect 10 cannabinoids in less than 11 minutes [224], and screen-printed electrodes carbon black is reported to be useful where the proportion of CBD is much higher than THC [225].

Additionally, literature has raised some serious concerns about the difference between labelled/declared and measured/observed amount of CBD/THC in various hemp products, for example, 9 out of 14 samples had a notably different amount of CBD than labelled [23], THC was detected in 5 out of 21 products which were claimed to be THC free [226], d9THC were detected above the limit of quantification in many unregulated products and in Epidiolex® [226], in some cases measured CBD (1.45–1.81%) was much lower than declared (5%) [227], and less than 50% of the samples contained cannabinoids within 20% of their label declaration [228].

3.5.4. Futures theme

Literature published in the last few years is starting to substantiate claims of hemp having substantial environmental benefits for a sustainable future, due to its potential for carbon sequestration and storage, lower ecological footprint, heavy metal accumulation potentials, and pollution control. A study carried out through a life cycle assessment approach concluded that carbon uptake (−1.29 kg carbon dioxide equivalent - $kgCO_2eq$) was much higher than carbon footprint (0.975 $kgCO_2eq$) for 1 kg of hemp hurd [229]. Additionally, a study reported the net carbon sequestration of 0.67 t/ha/year by industrial hemp crop [230]. Hemp is also reported to reduce land use competition and improve environmental quality [231] by improvement of soil health [232], stabilizing clayey soils [233], suppressing weeds [234] and enhancing soil organic carbon during field retting [235]. It is considered as a low-input low-impact crop against other agricultural crops [236]. Hemp could be used for environment-friendly botanical insecticides, especially to repel mosquitoes, aphids, flies, and other agricultural pests [237–239]. Yet, some authors pointed out that hemp is also associated with some environmental challenges, such as acidification and eutrophication of water systems [240]. Processing plant of hemp is reported to produces bleachery effluents [241], and a study also reported its potential threats on human health due to heavy metal contamination in end products [242]. Phytoremediation potentials of hemp has been rigorously discussed in many literature, with the characterization of heavy metals (i.e., Pb, Zn, Cd, Ni, Cr, and Cu) and proportional accumulation in different parts of the plant [243–245]. Some authors proport that hemp is not a hyper-accumulator but a heavy metal tolerant species which can be grown in moderately contaminated soils [244,246]. A study claimed that heavy metal concentration in hemp fibre is below the threshold for the textile industry [247], while another study was concerned with the potential threat of heavy metal accumulation as it exceeded the safety limits of Co, Cu, Cr, Ni, and Pb [248].

Studies on future market potentials claimed that it should be considered for a dual-purpose growing model, whether it be for fibre and seed [249], or natural products (i.e. cannabinoids and terpenoids) and bioenergy [250], or valorisation of residues [251,252]. A study in New Zealand found that hemp fibre can be grown at a much lower price than the price of imported fibre [253], while another study claimed that even biomass residue can return as high as EUR 9364/ha/year through volatile fatty acid production [251]. About 43% of the hemp farms are using marginal abandoned lands in Italy [254] and hemp is claimed to yield three times more fibre than cotton with a reduction of cost by 77.63% compared to it [255]. However, the instability of the market and production efficiency remained the challenges [256], for example, dried flowers which were the most common product in North America dropped from 81% to 73% in Canada and 78%–72% in the USA between 2018 and 2020 [257]. Legislative clarity and an enabling policy environment [258–261], research funding for hemp agronomy and industry [262], fostering local investors and community supply chain [263,264], economic subsidies and incentives [265], and easy access to private banking and investment [266] were the common threads in policy discussion. An integrated approach of agronomic expertise, blockchain (supply chain planning), and digital technology (i.e., Internet of Things) [267] have been suggested to overcome the potential challenges associated with the increasing trends of non-prescriptive use of CBD in dietary supplements without detail research on its phytochemical and pharmacological effects [268] as well as potential political interference which can have a profound impact on human health [269].

There have been very few studies about the analysis of research and education in hemp industries. Yet, few studies mentioned research priority (i.e., market and regulatory compliance) from the stakeholders' perspective [270], consumers' interest and response (the more information the higher the acceptance) to the hemp products in market [271], and legislative gap and lack of expertise as the challenges for farmers and growers [272,273]. Besides, we found an attempt at dataset development for hemp cultivation, along with the yield map and cost-benefit ratio, in Malaysia [274]. Increasing trends in hemp research, political commitments, and the interests of farmers to be certified growers have postulated sufficient space for hemp industry to foster the future agronomic transformation and the development of sustainable hemp industry [270,271,275].

4. Discussion

4.1. Reflecting on the research trends and research orientation

Research on hemp has been accelerating, notably since 2016 (Fig. 2). While a few studies were published after hemp was legalized for production with low THC in some European countries and Canada [276], the majority of studies were published after it was allowed for commercial cultivation in USA [3]. The growing number of publications indicates that hemp is now revitalized as an emerging crop in the agronomic industry [277–279]. Although a total of 58 countries were found to be publishing hemp research, most reports were concentrated in North America, some European countries, and China, with a very low proportion in South America, Africa, the Middle East, and Asian countries (Fig. 3). This might be because of multiple reasons, for instance, lack of consistent research protocol to detect cannabinoids [16], overestimation of risks and inadequate public education [17], poor research funding [127], uncertainty in the supply chain [20], and lack of political confidence and legislative gaps [272,273].

Moreover, prohibitionist policies and legal restrictions for hemp cultivation associated with lack of adequate resources and technical requirements to ensure transparent supply chain and quality control are reported as reasons for the lack of research and development of hemp in global south [17,280,281]. Similar to our findings, a review by Liu et al. [27] found that 62 countries were involved in studying cannabis and CBD, but they identified the USA, UK, Italy, Brazil, and Canada as the top researching countries whereas in our case China, France and Poland were top researching countries after USA, Italy and Canada. Their review considered the articles only about 'cannabis and CBD' and limited their review until 2019. But in our case, $<50\%$ of the selected articles were published before 2019. Although hemp has high variability according to the origin of the cultivar, climate, and other environmental factors [173,282], it has been studied throughout different regions of the world, implying its potentially global market and wider supply chain network.

We found that hemp has been studied from multiple perspectives, ranging from agricultural science to material science, energy, medicine, pharmacology, environmental science, chemistry, and even in the stream of computer science. This wide coverage of hemp cultivation signifies the wider scope and applicability of hemp research and development. However, most of the publications are found to be concentrated on agronomy (germination and plantation techniques), material science (fibre and fuel), and chemistry (cannabinoids), leaving various important aspects of economic potentials, supply chain, and sustainable development sectors from hemp industry [20,26,27]. Although research on hemp has been published in numerous journals (n = 301), most of them were fibre-based journals (i.e., Industrial Crops and Products, and Journal of Natural Fibres). Congruently, a previous review found that 1167 articles on hemp were published by about 497 different journals [27]. Consideration of hemp in multi-disciplinary journal articles (Table 2) indicate increasing recognition of hemp for medicinal application, food ingredients, material and bioenergy application, and various other environmental and economic development sectors.

4.2. *Discussing hemp champions: opportunities and challenges*

Our SLR also validated that hemp is a versatile and multipurpose plant with more than one-third of the articles focussing on the whole plant (or multiple parts of the plant) usage and a similar proportion of the articles focused on the multipurpose application of hemp rather than a single product of interest from a specific part of the plant (Fig. 5). Consideration of the whole hemp plant and its multiple uses has also been supported by previous literature [1,67,283]; however, a substantial proportion of research articles considered only the plant stems (i.e., hemp fibre), secondary metabolites from the plant (mostly cannabinoids), and hemp seed. Although hemp fibre dates thousands of years back [26], the chemical structure of CBD (including other secondary metabolites) and its application has been studied only since the 1970s [284]. Research articles with a single product of interest, indicated medicinal applications, composite materials, and food ingredients as their priority research topic. This scenario might indicate that although hemp is considered for its versatility; CBD, fibre, and seed oil are the hemp champions with regards to its agronomic efficiency and economic viability. Prohibition and legislative uncertainty have hampered hemp research and development [285,286]; however, it has been growingly recognized for its unprecedented medicinal and food applications.

We can infer two pathways of industrial hemp production: competitive single use or multipurpose production model. First, competitive hemp products can be derived when agronomic, processing, and industrial practices are adopted based on the champion single product. For instance, the choice of fibre quality, cannabinoids production, and quality of hempseed oil and protein depends on genotype selection [60,287,288]. Likewise, some scientists believed that the choice of cultivars affects the champion products, such as Beniko, Fedora 17, and Futura 75 are considered the best for fibre, seed oil, and CBD content, respectively [65,69,289]. Similarly, the application of fertilizers is highly recommended if the target is fibre quality and biomass production [44–46], otherwise, fertilization is supposed to have an insignificant impact on the productivity of CBD and/or seed oil [48–51]. Accordingly, harvesting time and techniques, processing methods, and manufacturing processes highly differ based on production feasibility and end use of the product [12,285,290].

Second, there is a growing consensus that the hemp industry will benefit if a dual purpose or multipurpose production model is adopted, value-adding to several end products including CBD, fibre, seed, bioenergy, or valorisation of other hemp residues [249–252]. A multipurpose production model is also recommended to mitigate potential market failure, legislative uncertainty of chemical constituents, and to combat with the misconception of hemp by allowing informed, rational, and science-based decisions [16,17,20,291]. Further, capitalizing on a circular economy model for hemp by prioritizing low carbon footprint and zero waste products and reconsidering the by-products and/or residue can be the best option to ensure economic efficiency and environmental sustainability [18,20,292]. Whatsoever, the blueprint production model of hemp can be misleading because it's functional genomic, agronomy and economy greatly varies across different geographic and temporal scales. So, the choice and production processes must depend on the availability of cultivars, the feasibility of advanced germination techniques, climate and environment, the scale of production, value addition, and market potentials of hemp products, which needs to be evident through rigorous research and development.

As noted, early wins of hemp can be CBD and seed oil for food and medicinal applications as well as hemp fibre for textiles and composite materials. Although we could further specify the end products from those champion products, it is too early to claim the end products because of the rapidly growing hemp market and versatility of hemp products against fragile consumer behaviour and uncertainty in the supply chain [266,271]. Rather, we believe it indicates that there is room for future research and review. Nonetheless, the therapeutic role of CBD is unique and immense including those for neurodegenerative disease and epilepsy, metabolic disorders, treating pain and emesis, inflammation, infectious disease, and over 12 different cancer types [293–296]. Furthermore, nutritional and nutraceutical benefits of seed oil because of its high level of essential and polyunsaturated fatty acids, including optimum ω-6/ω-3 ratio, vitamins, and minerals are acknowledged for its higher digestibility, low allergenicity, and diverse functional properties [297–299]. Some authors claimed that if tobacco can be regulated, hemp can also be properly regulated for its chemical constituents by ensuring quality control and traceability and monitoring of the supply chain [268,300]. However, the chemical composition and quality of the products depends not only on the extraction and processing techniques but also on the initial quality of plant material, harvesting time and techniques [301]. Lack of *in-vivo* studies to examine the administration and effectiveness as well as the lack of evidence of therapeutic efficacy of CBD [302,303], and drug-drug interaction, possible adverse effects and toxicity of *in-vitro* and *in-vivo* ingestion further add challenges to the food and medicinal application of hemp [304]. In this regard, although hemp has immense potential for economic development and human health, it must be guided and well-regulated through evidence-based clinical trials and scientific research.

Regarding the historical use of hemp, Şakiroğlu [305] reported that hemp was regulated in the Ottoman era, especially for fibre to use for textile and boat building material, as well as hemp seed as a grain and as an oil source. The application of hemp has been diversified with the diversifying modern industries capturing its versatile potential use. Because of its good mechanical, insulation, and acoustic properties as well as low-impact production possibilities, hemp could transform future generations of structural engineering with its novel application in paper and textile, consumer goods, load-bearing packaging material, and non-load-bearing construction applications [153,155,290,306]. A study estimated that hemp fibre can exhibit the highest annual market value of about EUR 2204–3746/ha [307]. Further, hemp fibre is a sustainable alternative to reduce conventional petroleum-based polymers [308] and to replace the cotton industry which accounts for one-fourth of the world's insecticide market [152]. Furthermore, according to an older study (in 1916), one acre of hemp was supposed to replace four acres of trees [309]. However, poor hydrophilic characteristics, incompatibility with other polymer composite matrices, and compromised compressive strengths are the challenges in the fibre market [290]. Although pre-treatment and adjustment of the proportion of hemp in composite materials could help to overcome the challenges [310,311], production and processing efficiency as well as product diversification must be critically examined through comparative research and development.

Numerous other applications of hemp include bioenergy, phytoremediation, hempcrete and construction applications, carbon sequestration, and other environmental benefits. Because of the higher cellulose content and low carbon footprint, hemp is considered a competent energy crop for bioethanol production [18,312]. An estimate showed the energy yield of green hemp can be as high as 296 Gj/ha from biogas and ethanol production about 2799–4503 l/ha from dry hemp stalk [313], implying higher scope for bioenergy. Yet, some authors did not see it as a sustainable solution because of the low market value of raw material [314], poor identification of optimal pathways for combined biorefinery production [307], and higher (minimum) selling price of the biodiesel [315]. Phytoremediation potentials of hemp are exceptional because hemp can accumulate various heavy metals (including Pb, Cd, Zn, Ni, and Cu) and organic contaminants (Benzo pyrene, Nephthalene, and Chrysene) [292,313,316], which contaminated about one-third of the global arable lands [242]. In addition, hemp can be used for the urban Phyto-cleaning as well as environmental purification of waste dump sites and industrial areas. Yet, safety limits of the heavy metals in food and medicines as well as compromised commercial application of hemp products grown in heavy metal areas pose serious concerns over this application [248,317]. Lightweight, standard insulation properties (inert to heat and moisture) [318], excellent deformation capacity [319], and carbon storage potentials [138] have made hemp (fibre/hurd/residue) a competent candidate for hempcrete for energy-efficient buildings [320]. An estimate of carbon budget claimed that a 30 cm thick hemp-lime can make a net storage (sequestration minus emission) balance of 36.1kgCO_2eq./square metre, claiming hempcrete as a 'carbon-negative' material [321]. But the low rate of compressive strength (3.5 Megapascal) and low density (200–840 kg/cubic metre) as compared to ordinary OPC concrete's 17 Megapascal and 2400 kg/cubic metre, respectively, have limited its application for load-bearing structure [321]. Yet, proper processing, pre-treatment, and use of additives and coating can make a wider application of hempcrete for energy-efficient, carbon-negative, and environmentally sustainable building infrastructures.

After examining the prospects and challenges of hemp application, it might be difficult to make a generic statement about the champion products of hemp. Yet, one thing is certain, hemp is a crop that grows like a weed (low input – low impact) with a short rotation period, but possess immense industrial opportunities in pharmacology, food supplement, and composite materials through the hemp champions, such as CBD, seed oil, and fibre, respectively. For example, application of CBD to interact with our endocannabinoid systems is reported to regulate various physiological processes. Similarly, use of hemp seed as a source of protein and food supplements has the potential to present in every kitchen (like caffeine). Additionally, environment-friendly fibre production from hemp has the immense potential for application in numerous composite material and textile industries. In this regard, we need to target the champion products in hemp industry, which can lead the other industrial applications of hemp. To illustrate the approach, the growing use of hemp for CBD production in United States has assisted the whole hemp industry to a better position of its research and development throughout the world, which has now triggered a discursive shift in hemp for health, environment, and economy. Nonetheless, we need to be watchful for the multi-purpose production model based on the availability of cultivars and knowledge of genetic engineering, climate and environment, agronomic practices, scale of production, and the scope of processing, manufacturing, and marketing. Based on our SLR, we argue that it is highly implausible to underestimate the environmental and economic potentials of hemp and we have no excuse to delay the capitalization of its benefits. However, we cannot speed the industrial growth without adequate research knowledge and evidence. Regarding this, we argue that legislative clarity, regulation of the whole supply chain to ascertain the quality and traceability of hemp products, building a sovereign supply chain, and sufficient clinical trials before human use of hemp products are the precursors to a sustainable hemp industry.

4.3. Research gaps and future research priorities

Recent literature focused on fibre, textile, and composite materials, comprised over one-fifth of the selected research articles (n = 139). Previously, phytochemical analysis and potency testing (n = 45), hempcrete and construction applications (n = 43), and germination and plantation techniques (n = 41) were the popular topics of research. Nevertheless, a substantial number of research articles cover wider thematic areas of hemp (Fig. 6) and provide a solid knowledge base for agronomic and economic practices for hemp growth (Supplementary File 2). Yet some classical reviews claimed that there is much more to do with research in hemp, including the developing hemp with high CBD and low THC [27,322], market demand for green products [26], addressing non-technical (i.e., legal) and technical (production efficiency and carbon footprint) challenges of hemp [20], and evolution of ongoing scientific debate and knowledge [17]. Based on our two-stage SLR, we have identified critical research gaps and research priorities which must be considered for the sustainable hemp industry.

The holistic research landscape of the champion products is missing, which is a crucial to link all five identified major themes of hemp. There has been a substantial number of studies, but on a piece-meal approach without a comprehensive research review of the whole hemp supply chain. To fill the research gaps, functional partnerships and engagement of various stakeholders (scientists, engineers, educators, industry leaders, medical communities, and policymakers) is required to underpin a sustainable hemp industry [17,323,324]. There is an ongoing effort through a an EU-funded project, MULTIHEMP, attempting to develop an integrated biorefinery and new opportunities for a hemp-based bioeconomy [14]. However, it was not adequate to capture the whole supply chain. In this regard, a common framework of research entailing a contiguous supply chain (from seed to seed) of hemp with robust research protocol is needed to deliver emerging opportunities from hemp. This requires a huge investment in the research and development of hemp. Additionally, theme-wise research needs are presented in the subsequent sections.

4.3.1. Hemp production

Early detection and easy differentiation of hemp varieties is crucial to overcome the legislative uncertainty and production of industrial hemp. Various efforts have been made for rapid identification of genes [57] and scientists have also developed advanced techniques (including 'omics approaches) to study phytochemical pathways [325], yet characterizations of its functions are not detailed which are needed to maintain genetic and metabolomic integrity. In line with our recommendation, previous studies have also outlined the importance of early detection of hemp varieties with detailed profiling of cannabinoids [16,285]. Additionally, there is a further challenge to integrate the profiling with bona-fide breeding programs. Regarding this, there is a lack of research and discussion about the classical breeding programs to improve desirable traits, selective breeding, and natural genetic variations [326,327]. Whatever, the approach of developing a consistent elite breed of hemp varieties, distinguishing it from its other close species might have three-fold implications, such as correcting inconsistent legislations and easing regulation of hemp products, consumer awareness and overcoming the negative perception of hemp, and helping quality control and minimizing the market uncertainties. Mass propagation of hemp through tissue culture is well developed; however, to better execute gene transformation and gene editing we require organogenesis, somatic embryogenesis, and haploid production [328] and also there is a lack of a robust set of Single Nucleotide Polymorphism and Simple Sequence Repeat markers which are required to assist breeding programs in future [329]. More research is needed to focus on next-generation sequencing and the use of fast-evolving gene editing tools to speed up the novel genes for large-scale CBD production [330]. Furthermore, there is a lack of core breeding efforts with clear product profiles to feed custom primary products into supply chains for different end markets.

Numerous studies have been carried out on agronomic practices, such as cultivar selection and appropriateness, fertilization, harvesting time and techniques, diseases and pests, and photoperiods (Supplementary File 2); however, research on broadacre cultivation, protective cropping, and sustainable farming systems are not sufficient. For instance, research gaps have been identified for post-cultural analysis of phytochemistry after acclimatization [330], overcoming auto-allelopathy for commercial production [331], differing fertilizer requirements for different end-products [332], the effect of abiotic stress on hemp production [333], improving traits to resist disease and pests, effects of the different light spectrum (other than white and blue) to get further insights into light-dependent regulatory and molecular pathways [334], and nutrient requirement for the plant grown in different edaphic and climatic conditions [335]. Furthermore, considering the variability of phytochemicals based on different breeds and external environmental factors, more research is needed to ensure sustainable farming, innovative cultivation and harvesting techniques, biosecurity, and integrated pest management.

4.3.2. *Hemp material*

Product diversification and multipurpose application of hemp come with the requirement of more research and studies on differing pretreatment techniques, bioactive extraction methods, and the processing of multiple products at different stages in the whole supply chain. Much of the past efforts have focused on seed oil and bioactive compound extraction, fibre treatment and extraction (Supplementary File 2), yet there is more to do with freeze drying and hydrodynamic extraction [336], cost-effective extraction and suitable encapsulation methods [302], mass transfer resistance and solubility of various compounds during extraction [337], the impact of climate, geography, and plant types (i.e., strain, chemovars, and chemotypes) on recovery phytochemicals [338], scaling up of the technologies for fibre modification for a commercial scale for paper, textile, and composite products [308], and blending of hemp fibre with global sustainability and environmental benefits [339]. Additionally, some reviews have identified research gaps in bioenergy applications, for example, analysis of long-term efficiency of bioconversion processes (i.e., gasification, pyrolysis, and anaerobic digestion) [127], characterization of lignin composition including its molecular weight [340], and chemical modifications of the lignocellulosic biomass [18]. Likewise, the relationship of plant origin to the compaction and other functional properties of hempcrete for its applicability to use with local aggregates and binders to adapt to local culture and climate is still missing in the literature [341]. In this regard, future research should focus on advancing post-harvest processing and exploring value addition techniques to the existing and new uses of hemp and hemp-derived products on a commercial scale in a sustainable manner, bonding backward and forward linkages among producers, manufacturers, and consumers. Furthermore, establishment of standards for production and processing of hemp products must be streamlined for sustainable hemp industry.

4.3.3. *Hemp for health*

The use of hemp for human health has been one of the most debated yet controversial areas of research, including findings about the transferability of cannabinoids, variability in measurement, and differences between labelled and observed contents of cannabinoids. Although numerous studies mentioned phytochemical analysis and quality testing of hemp, standardization and optimization of phytochemical analysis is inadequate. For example, rapid profiling of secondary metabolites and their upscaling from laboratory to industrial scale is lacking [323]. There is a lack of research on developing a robust approach to combine mass spectrometry with bioinformatics and chemometrics [342]. Preclinical and clinical characterization as well as storage stability of CBD is an emerging field of research, and there is a need for well-designed, randomized, placebo-controlled, and double-blind clinical studies to validate the health benefits of hemp-based products [304,343–345]. Regarding food supplements, the functional properties and flavour profile of hemp protein as well as its solubility and biocompatibility with other food components are yet to be determined [346–348]. Rigorous research in hemp-based protein products and amino acids to ascertain its quality and to institutionalize the production process for human consumption is an emerging need. Although there has been few efforts in establishing patents and intellectual property rights [349–351], still the efforts are inadequate to develop and institutionalize patents over various hemp products and processes. A robust set of research protocols for rapid profiling of cannabinoids at different stages of processing and packing of hemp products, upscaling of laboratory findings to industrial scale, and rigorous pharmacological testing and clinical trials must be carried out to ensure the safety and efficacy of hemp for its therapeutic, nutraceutical, and nutritional use.

4.3.4. *Hemp futures*

The future of hemp industry is dependent on the regulation of hemp products, market structure and potentials, and nature sustainability through industrial hemp. For example, little is known about policy mechanisms and institutional arrangements for the regulation of hemp products and to harmonize country/state level legislative instruments. The regulatory framework of countries might vary based on their political, historical, and socio-cultural factors [17]. More research is required to show scientific evidence about the effects and toxicity of hemp products for the development of a minimum common standard to regulate hemp, which can be eased by global institutions, such as the World Health Organization and the World Trade Organization. There have been some hypothesized estimates about the market potentials of the global hemp industry [26,352], however, less is known about the public demand for green products and the tussle of a new-comer to the hemp industry with the already established fibre market (i.e., cotton industries) and colonial medical systems. A traceable and transparent hemp supply chain is important to build confidence for farmers and to increase acceptance for consumers [267]. The use of digital technologies and artificial intelligence to boost agronomic efficiency, supply chain planning through blockchain technologies, and modelling are yet to be captured. Few studies can be found about the role of hemp in carbon sequestration [12,321], but an emerging benefit of hemp to minimize land use pressure is not explored. Similarly, numerous studies have quantified the phytoremediation potentials of hemp but the downstream effect of the heavy metal contents in various hemp products is still not known. Although valorisation of hemp residues is populated in the literature [251,307,312], studies are inadequate to assure zero waste across the whole supply chain and build a circular economy of industrial hemp. A rigorous analysis of life cycle assessment of hemp is missing which is most needed to ascertain carbon negativity and circular economy for sustainable futures. Besides, education and research programs need to be intensified in different sectors to develop a sustainable hemp industry through a synergistic effort from scientists, academicians, producers, manufacturers, marker actors, and policymakers.

4.3.5. Limitations and opportunities

Having discussed the hemp products with high potential and the research priorities based on our review, we acknowledge a few limitations associated with our SLR. We depend on only two literature databases (Scopus and Web of Science); the use of more databases would include more research articles. The language of the papers was limited to English, so some relevant papers might not be included in this SLR. The selection of keywords and search string were to balance specificity and sensitivity in the literature search. In this regard, we advise the readers to consider the keywords while generalizing the findings of our review. Because we have reviewed the article from a broader perspective, zooming into each theme or sub-theme of the research is recommended to get deeper insights into the knowledge findings and specific research gaps. Nevertheless, building on a sound methodological framework with the novelty in SLR through a two-stage review, this paper provides a comprehensive knowledge base as well as knowledge gaps throughout the supply chain of industrial hemp. We argue that CBD, seed protein, and fibre are the low-hanging fruits of industrial hemp, but the adoption of a priority-based multipurpose (or at least dual-purpose) growth model is necessary to sustain the hemp industry. In addition, the proliferation of a broader research landscape entailing the whole hemp supply chain, early detection and differentiation of elite hemp lines, improved agronomic practices and broadacre cultivation, advancement and scaling up of product processing and extraction methods, standardized procedures of phytochemical testing and quality control, enabling policies and predictive legislations, use of digital technologies, and circular economy of hemp are the immediate research priorities. Functional partnership and collaboration among scientific communities, industry professionals, policymakers, and market actors can capitalize the immense economic and environmental opportunities of hemp through a secure and sustainable hemp industry.

5. Conclusions

A piece-meal research approach and sectoral review of industrial hemp have provided a compelling reason for a comprehensive and multi-stage review of hemp research to enable knowledge mapping for the sustainable hemp industry. We selected and reviewed a total of 756 (101 reviews and 655 research) articles on different aspects of industrial hemp, covering multiple dimensions under the broader five thematic areas, namely, production, material, health, futures, and education and research. Although hemp has been cultivated for thousands of years, the research on hemp has been exponentially accelerated in the last five years. Over one-third of research articles claimed hemp for multipurpose applications by the use of whole or multiple parts of the plant. Hemp is a versatile plant, yet cannabidiol, fibre, and seed oil were found as the hemp champions. The unique therapeutic role of cannabidiol in treating neurodegenerative disease and epilepsy, metabolic disorders, treating pain and emesis, inflammation, infectious disease, and cancer has been regarded as the broader medicinal applications of hemp. Similarly, nutritional and nutraceutical use of seed oil, especially due to its higher digestibility and optimum ω-6/ω-3 ratio, vitamins, and minerals, has become an emerging market for industrial hemp. However, inadequate studies on drug-drug interaction, and possible adverse effects and toxicity of *in-vitro* and *in-vivo* ingestion are the crucial factors to monitor for medicinal applications of hemp. Additionally, excellent insulation and acoustic behaviour as well as good mechanical properties of hemp fibre make it a perfect destination for paper and textile, consumer goods, load-bearing packaging material, and non-load-bearing construction applications. Hemp fibre has the high potential to reduce land use competition, deforestation, and the high-environmental impact cotton industries. However, the hemp industry needs to overcome poor hydrophilic characteristics, incompatibility with other polymer composite matrices and compromised compressive strengths of hemp fibre. To address potential market failure, legislative infancy, and limited consumer awareness, a multipurpose production model is recommended for the sustainable hemp industry.

Hemp can be a superhero in solving some key human challenges, such as land use competition, industrial pollution, global food crisis, carbon emission, and energy issues. However, studies on hemp were found to be concentrated mostly on fibre and composite materials, followed by phytochemical analysis, hempcrete, and plantation techniques. Our review depicted critical research gaps and priority research areas to be considered for future studies: (1) future research should focus on assessing whole hemp supply chain, covering all five thematic areas of hemp research because current studies are inadequate to capture the holistic research landscape of hemp industry, (2) research on hemp production should focus on precise detection and differentiation of hemp varieties to maintain genetic and metabolomic integrity, next-generation sequencing and fast-evolving gene editing tools, broadacre cultivation, protective cropping, fertilization, and sustainable farming systems, (3) industrial scale cost-effective extraction and encapsulation of bioactive compounds, scaling up of fibre modification technologies, characterization of lignin composition and modification of lignocellulosic biomass, advancing post-harvest processing and value addition techniques are emerging research needs in hemp material, (4) studies should further consider standardization of phytochemical analysis, rapid profiling of secondary metabolites, tools to combine mass spectrometry with bioinformatics and chemometric, and rigorous pharmacological testing and clinical trials, and (5) policy studies on hemp regulation, economics and market structure, social survey about public demand of green products, and carbon accounting studies of hemp life cycle might pave the roadmap for sustainable hemp industry.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cscee.2023.100550.

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