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REVIEW

Enviro-economic and feasibility analysis of industrial hemp value chain: A systematic literature review

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Abstract

A recent renaissance of industrial hemp has been driven by a plethora of ecologically amicable products and their profitability. To identify its environment and economic fate across the value chain (VC), this study conducts a systematic review of 98 studies published in ScienceDirect, Web of Science, and Scopus-indexed journals. The thematic content of the articles is categorized using three deductively derived classification categories: lifecycle analysis ($n=40$), VC analysis ($n=30$), and feasibility analysis ($n=28$). Bibliometric analysis indicates that the majority (>90%) of the studies were conducted in selected regions of Europe or North America, with further findings around regionally prioritized industrial hemp products, such as hempcrete in Southwest Europe, solid biofuel in North European states, and textile fiber and bio-composites in East Europe and North America. Lifecycle analysis studies highlight nitrogenous fertilizer use during industrial hemp cultivation as a major ecological hotspot, which is taking a toll on the climate change index. However, hemp-based products are generally climate-friendly solutions when contrasted against their fossil fuel counterparts, with hempcrete in particular a highly touted carbon-negative (−4.28 to −36.08 kg CO_2 eq/m^2) product. The review also identifies key issues within the hemp VC and presents innovative solutions alongside the recognition of value-adding opportunities. Furthermore, feasibility analysis indicates unprofitability in using hemp for bioenergy production and there is a relative cost worthiness of hemp bio-composites and hempcrete at the upstream level. Positive returns are observed under co-production schemes. In contemplating the literature findings, we discussed and identified gap in existing literature for future exploration, including more studies to provide insights from the Global South, and the production of industrial hemp under a biophysically constrained landscape.

KEYWORDS
enviro-economic, feasibility, industrial hemp, systematic review, value chain

1 | INTRODUCTION

Cannabis sativa L., synonymously called "hemp," is a prehistorically iconic crop, heralded for its millennia-old source of utility fibers, foods, and pharmaceuticals (Farag & Kayser, 2017). In Europe and East Asia, as "Industrial hemp," it was introduced and grown as a prolific fiber-bearing crop having only an iota of intoxicating Δ^9-tetrahydrocannabinol (THC) (Clarke, 1999). However, due to its morphological similarity to THC enriched drug (marijuana) biotypes (Yang et al., 2020), most countries imposed a blanket ban on all *C. sativa* forms at the beginning of the 20th century (Cherney & Small, 2016). After the initial six decades of the 20th-century government prohibition, interest in this prehistorically iconic crop reignited globally, in part due to the recognition of a diverse range of hemp products (Dhondt & Muthu, 2021).

Some estimates have identified a repertoire of 25,000 industrial hemp-based products derived from its seed and biomass (Fike, 2016). Hemp seeds have more of a nutritional and therapeutic value (García-Tejero et al., 2019), while the fiber-rich stem (outer phloem fiber and inner xylem wood) of hemp biomass is deemed economically valuable (Cherney & Small, 2016; Kremensas et al., 2017). The latter is due to a diverse range of applications for biomass, ranging from textiles (Gedik & Avinc, 2020; Pergamo et al., 2018), to construction (Kallakas et al., 2018; Liao et al., 2022; Martínez Martínez et al., 2022; Yadav & Saini, 2022), and to the automobile industry (Chen et al., 2017).

Accrued global interest in industrial hemp is not just because of its myriad of products, but also for its capacity to provide eco-friendly alternatives that lower over-reliance on conventional fossil-based materials (Summit, 2020). For example, textile quality hemp fiber has potential to lower the dependency on both fossil-derived synthetic fibers (Aishwariya & Jaisri, 2020) and (water and fertilizers) input demanding cotton (Abbas et al., 2022). Additionally, the use of lightweight hemp fiber-built components in vehicles (Chen et al., 2017) in lieu of glass or carbon fibers can curtail petroleum oil consumption (Nachippan et al., 2021), with a subsequent reduction in climate relevant CO_2 emissions (Wazeer et al., 2023).

However, like most bio-based products, industrial hemp can have agricultural input related consequences, such as eutrophication and ozone layer depletion during the biomass cultivation phase (Weiss et al., 2012). There is also the impact of land use change on greenhouse gas (GHGs) emissions (Lange, 2011). As is common across the wide categories of bio-based products (Zuiderveen et al., 2023), hemp-based products may also have variation in their environmental impacts. Therefore, the sustainability of hemp products should be assessed individually and thoroughly. This involves examining the whole product value chain (VC), from cultivation, to processing, to manufacturing, to use, and, finally, to disposal (Zuiderveen et al., 2023). To this end, life cycle assessment (LCA) offers a methodological tool to quantify environmental impacts related to the entire production chain of a product (Tukker, 2000). During the conduct of LCA, important phases of a product are divided into segments to enable the meticulous examination and recording of data related to the most significant inputs and outputs around resource and energy (Rebitzer et al., 2004). Then, based on the types and magnitude of input used, output impact categories (e.g., climate change impact, eutrophication, and ecotoxicity) are quantified.

So far, LCAs have been utilized across numerous hemp-based products, including hemp-for-textile fibers (Van Eynde, 2015), hemp-reinforced automotive parts (Wötzel et al., 1999), hemp-based insulation solution (Zampori et al., 2013), and hemp shives for ethanol production (González-García et al., 2012). Some assessments also include life cycle costing (LCC) to estimate the economic aspects across the life phases (Harvey et al., 2016; Mastura et al., 2018; Torres-Rivas et al., 2018). The systematic integration of evaluated results on individual hemp products helps make a lucid statement about the sustainability performance of particular products compared to other bio-based or petrochemical substitutes. Regarding this, some specific reviews on products, such as hempcrete (Di Capua et al., 2021; Füchsl et al., 2022; Ingrao et al., 2015), hemp fiber composites compared with glass fibers (Shahzad, 2012) and reinforced composites (Manaia et al., 2019) have been conducted. However, a comprehensive systematic review quantifying the environmental effects associated with a range of hemp products compared with other bio-based and fossil fuel alternatives has not yet been performed.

The recent development in the hemp sector has also garnered the interest and involvement of various economic actors and stakeholders, resulting in the value chain analysis (VCA) of industrial hemp becoming another field of interest (Ceyhan et al., 2022). As such, due to this rapid evolution of the hemp industry and with multiple hemp products (Aryal et al., 2023), the economics of hemp has become more complex, leading to economic uncertainties among the VC actors (Mark & Will, 2019). Thus, a study that aggregates global VC knowledge pools can help identify market economic products, improve economic attractiveness of the products, and increase opportunities within the hemp VC.

Scientific queries on the feasibility analysis of hemp seed and fibers (Aydoğan et al., 2020; Fortenbery & Bennett, 2004; Fortenbery & Mick, 2014; Hanchar, 2019; Schluttenhofer & Yuan, 2017) show regional variability in profit (Dogbe & Revoredo-Giha, 2022; Johnson, 2013). Additionally, many studies (e.g., Brar et al., 2022; Finnan & Styles, 2013; Prade, 2011; Rehman et al., 2013) are unequivocal about the economic benefit of hemp feedstocks for bioenergy generation. Recent studies comparing the cost efficiency of manufactured hemp-based products against the slew of bio-based and synthetic bio-based products has resulted in ambiguity about the relative competitiveness of individual hemp products. So, the recognition of regional feasibility, actual fate, and relative competitiveness of industrial hemp products needs careful consideration.

To address these issues, this study aims to systematically review the current state of research articles that focus on the environmental and economic facets of industrial hemp products and associated VCs. The specific objectives are to (a) identify and document key bibliometric information of ongoing studies on the topic under consideration; (b) analyze the industrial hemp VC from an economic and environmental perspective based on the analysis and synthesis of emerging literature; and (c) find the research lacuna where further studies are needed.

2 | METHODS

2.1 | Classification framework

The study considers VCA, LCA, LCC, and economic feasibility analysis of the hemp value/supply chain and associated products. The deductively derived classification framework for analysis, consistent with the objectives of the study, is presented schematically in Figure 1. While VCA is a wider concept that analyses different phases (e.g., raw material extraction, processing, manufacturing, transportation, use, etc.) of the products, LCA components (of VCA) examine environmental impacts as they pass through these phases. VCA can typically capture the economic dimension of the products along the chain from the financial perspective (Maraseni et al., 2018). However, based on the assumption that hemp VC studies are in their early stages, we propose further classification bubble to assess the economics of individual hemp-based products. Thus, three classification bubbles evaluate the enviro-economic aspects of industrial hemp chains.

2.2 | Systematic review and protocol

This systematic review adopts the reporting protocol called the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA; Moher et al., 2010). Key characteristics of a systematic literature review are that it minimizes the authors' propensity towards the research topic, ensures replicability, and imparts clarity in the review and synthesis process (Lau & Kuziemsky, 2016; Grant & Booth, 2009; Mengist et al., 2020). In addition, PRISMA is a robust reporting format prominently used in health sector research (Liberati et al., 2009), while also gaining in popularity in research realms such as social and agriculture sciences research (Nor Diana et al., 2021).

2.3 | Eligibility criteria

The list of eligible articles considered for final review was guided by the PICO (Population Intervention Comparison

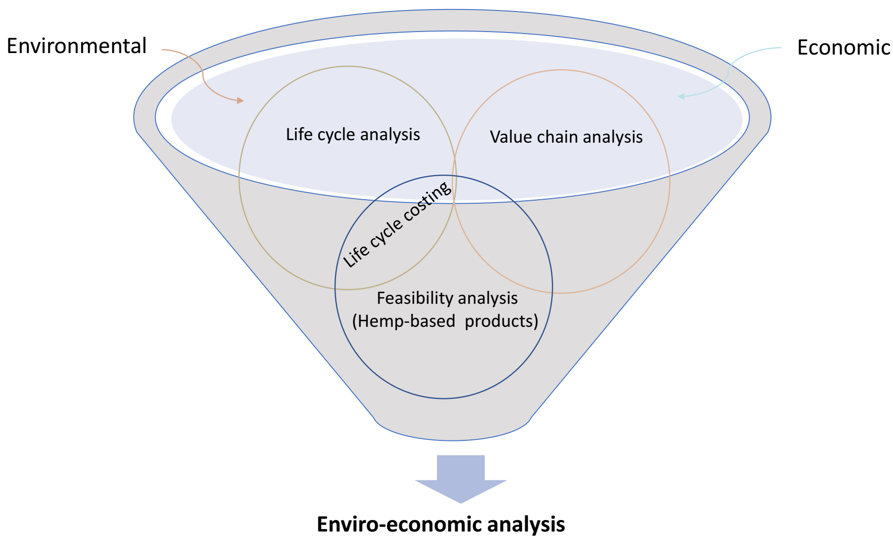

FIGURE 1 Classification framework for enviro-economic analysis of industrial hemp.

and Outcome) framework (Methley et al., 2014). PICO is a tool that originated from health and allied sciences to critically search and assess relevant literature (Eriksen & Frandsen, 2018). We modified the decision criteria of the PICO scheme in our context to remain within the scope of our study (see Table 1). We discarded all articles that considered medicinal, and pleasure uses of hemp, only populating our results with studies related to industrial hemp use. In subsequent rounds, the articles that dealt just with products physical or mechanical properties characterization were dropped and those studies with intervening parts leading to improvements in product value were considered. Then, we excluded perspective and narrative papers with no formal comparators. During our inclusion stage, we retained literature with approaches that compared industrial hemp products against alternative bio-based and synthetic products, demonstrated spatial comparison across nations or landscapes, compared different production processes and/or factors such as inputs use and edaphic conditions. Finally, the outcome criterion was comprised of results showing the qualitative and quantitative variations concerning the comparators or the intervention.

2.4 | Search strategy and article screening

Three online database platforms were used with the aim of extracting the maximum number of relevant articles: (1) Web of Science (WOS); (2) ScienceDirect; and (3) Scopus. Both ScienceDirect and Scopus are internationally acknowledged databases that index the largest number of scientific articles across the globe (Bhattarai et al., 2022; Karki et al., 2021; Maflahi & Thelwall, 2016; Meechang et al., 2020). WOS was used due to the high prevalence of agriculture-related articles (Mongeon & Paul-Hus, 2016) and to acquire related articles not found in the previous two databases. Identical search strings of ("cannabis" OR "hemp") AND ("chain" OR "LCA" OR "economic" OR "financial" OR "profitability" OR "feasibility") were applied to the title and/or abstract and/or keywords fields (see Table 2) to source the repertoire of articles. There was no restriction on the publication year and included English peer-reviewed articles only. Initially, these databases yielded 8684 hits of publications, which were then narrowed down to 7864 hits by applying a database filter to include only research, review, and data papers. This list

TABLE 1 Population, intervention, comparator, and outcome (PICO) framework for inclusion and exclusion decision.

	Included	Excluded
Population	Articles related to industrial hemp	Articles of therapeutic and recreational cannabis
Intervention	Technological, scientific, or policies leading to improvement in production chain and product value	Hemp-based product characterizations
Comparator	• Intercomparison between alternative products • Spatial (between different geographical locations) • Comparison within hemp genotypes, hemp-based products, under different climatic and edaphic conditions	Opinion papers; perspective papers; narrative reviews
Outcomes	Articles focusing on how strategic shift leads to knowledge creation; position relative to the comparators (outputs)	

TABLE 2 Combinations of keywords and Boolean operators for literature search.

		Title-abstract-key words
Operator	**Aspect of analysis**	**Boolean**
OR, AND	Value chain analysis from enviro-economic perspective	("cannabis" OR "hemp") AND ("chain" OR "LCA")
	Economic feasibility analysis	("cannabis" OR "hemp") AND ("economic" OR "financial" OR "profitability" OR "feasibility")

was imported into the Zotero library and, using deduplication, the number of hits was reduced to 5906. A subsequent 199 articles remained after manually screening at both the title and abstract level. Finally, after the full paper screening process, 98 articles published from 2003 to 2023 were considered for an extensive review process (see Figure 2).

2.5 | Bibliometric analysis

In this step, the included articles were descriptively characterized to establish a foundation for evaluating them across different themes. This analysis encompassed the distribution of articles by journal, spatiotemporal distributions, regional distributions of hemp products, and wise segregation based on approach and methodology.

2.6 | Categorical identification

In first step, selected studies were classified across the deductively derived categories (i.e., VCA, LCA, and feasibility analysis) based on the evaluation of the abstract and key findings. Next step involved identification of key research themes through inductive analysis of the content of each article. The outcomes were then synthesized, evaluated, and discussed within the established themes.

3 | RESULTS

3.1 | Bibliometric overview

The 98 articles deemed eligible for this systematic review were published in 52 different journals (see Figure 3). The Journal of Cleaner Production held the maximum record of publications (11), followed by Industrial Crops and Products with nine publications. The third most prolific one, the Journal of Industrial Hemp (seven publications), surprisingly published related articles for only until 2009.

As shown in Figure 4, the included articles were published between 2003 and 2023 (22/3/2023) and more than half (52%) of the total number of articles were published from 2019 onwards. Out of the total, 40 articles dealt with the LCA of industrial hemp, while 30 and 28 articles were related to the VC and feasibility analysis categories, respectively.

The spatial distribution of selected articles (Figure 5) shows that, more than 90% of the studies were conducted in European Union (EU) states, particularly Italy and France, and North American countries the United

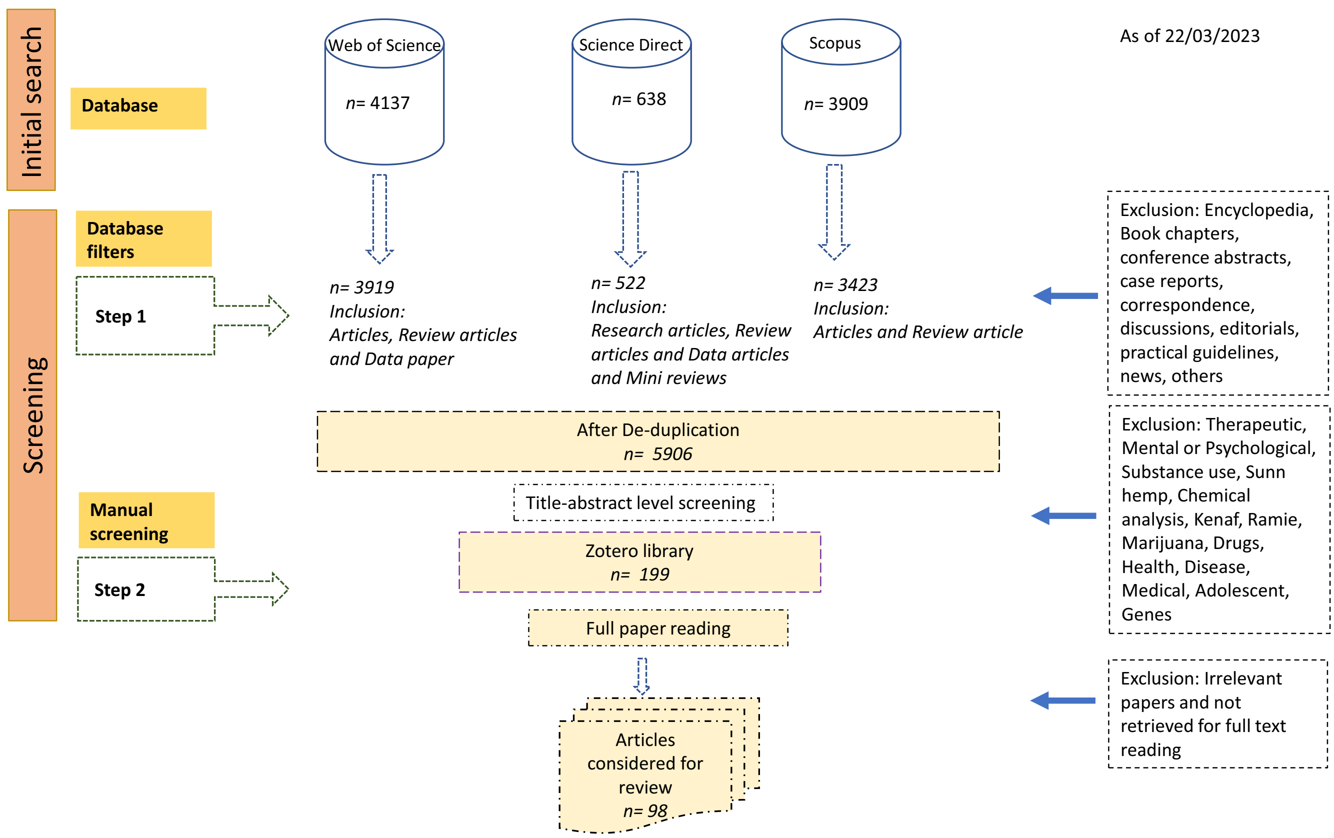

FIGURE 2 Literature search and screening process.

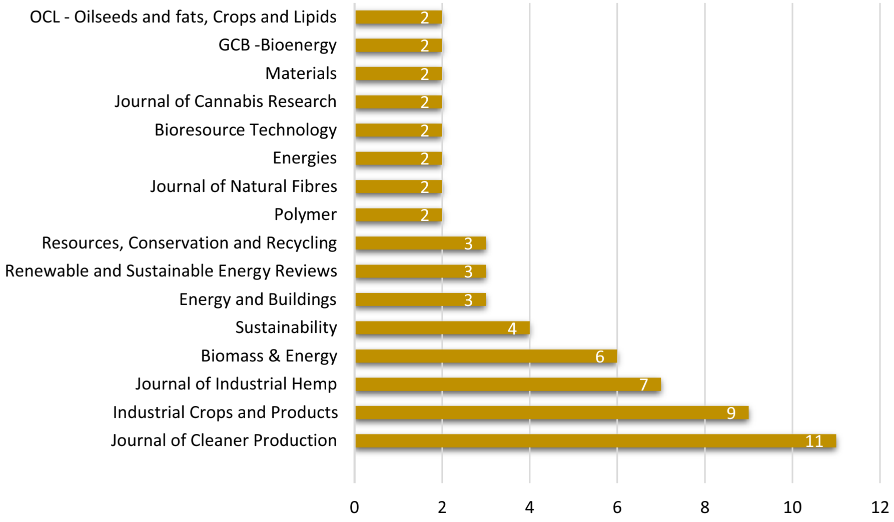

FIGURE 3 Journal-wise distribution of published articles.

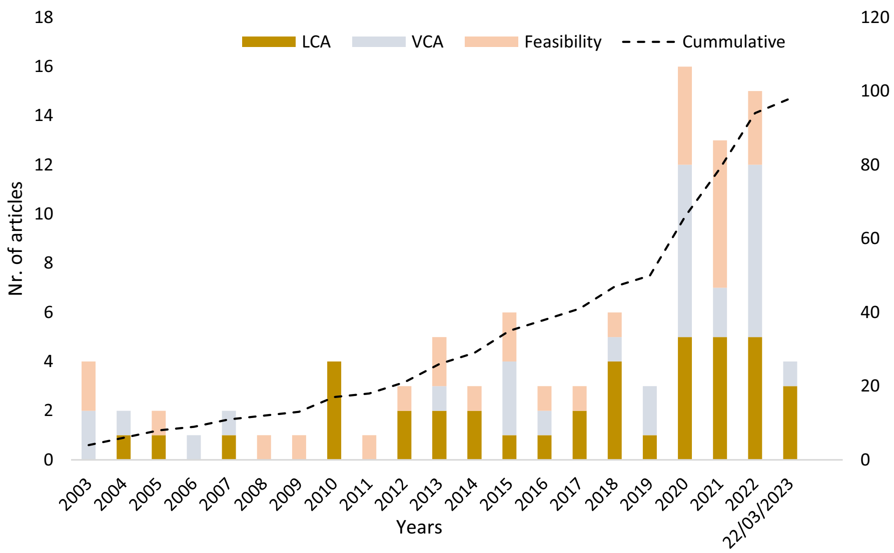

FIGURE 4 Annual distribution of articles across the domains of analysis ($n = 98$).

States and Canada. Very few (<4%) studies emerged from the Global South with no research from Africa or South America.

Figure 6 illustrates the regional distribution of hemp-based products based on the bibliometrics analysis of the articles, highlighting their regional prioritization. In Western and Southwest Europe (e.g., Italy), hempcrete received more attention, while Northern European states also emphasized solid biofuel alongside hempcrete. East European countries, namely, Hungary and Poland, focused mainly on textile fiber, while in North America, bio-composites seemingly received more research priority.

The research approach and methodology employed by the researchers are presented in Figures 7 and 8, respectively. Across both the VC and feasibility dimensions, the highly sought-out research approaches were experimental designs with an empirical nature. In particular, field and laboratory-based studies were used, in which researchers investigated ways to enhance the economic value of hemp products. Similarly, based on the empirical evidence the products were valued mostly in financial terms (see Annex 3). Researchers then used content, modeling, case-based or other approaches to descriptively analyze the topics, explore new ideas, and, to a lesser extent, prescribe future recommendations. Meanwhile, all LCA studies followed a common systematic LCA approach and methodology (see Annex 1) to evaluate the environmental impacts of hemp products against other product substitutes. These studies mostly assessed from cradle (materials extraction) to gate (manufactured product outlets) segments of the product's life across several indices, such as global warming potential, eutrophication, and fossil fuel depletion.

3.2 | Categorical identification

In this section, we inductively categorized articles based on the emerging themes across a deductively derived

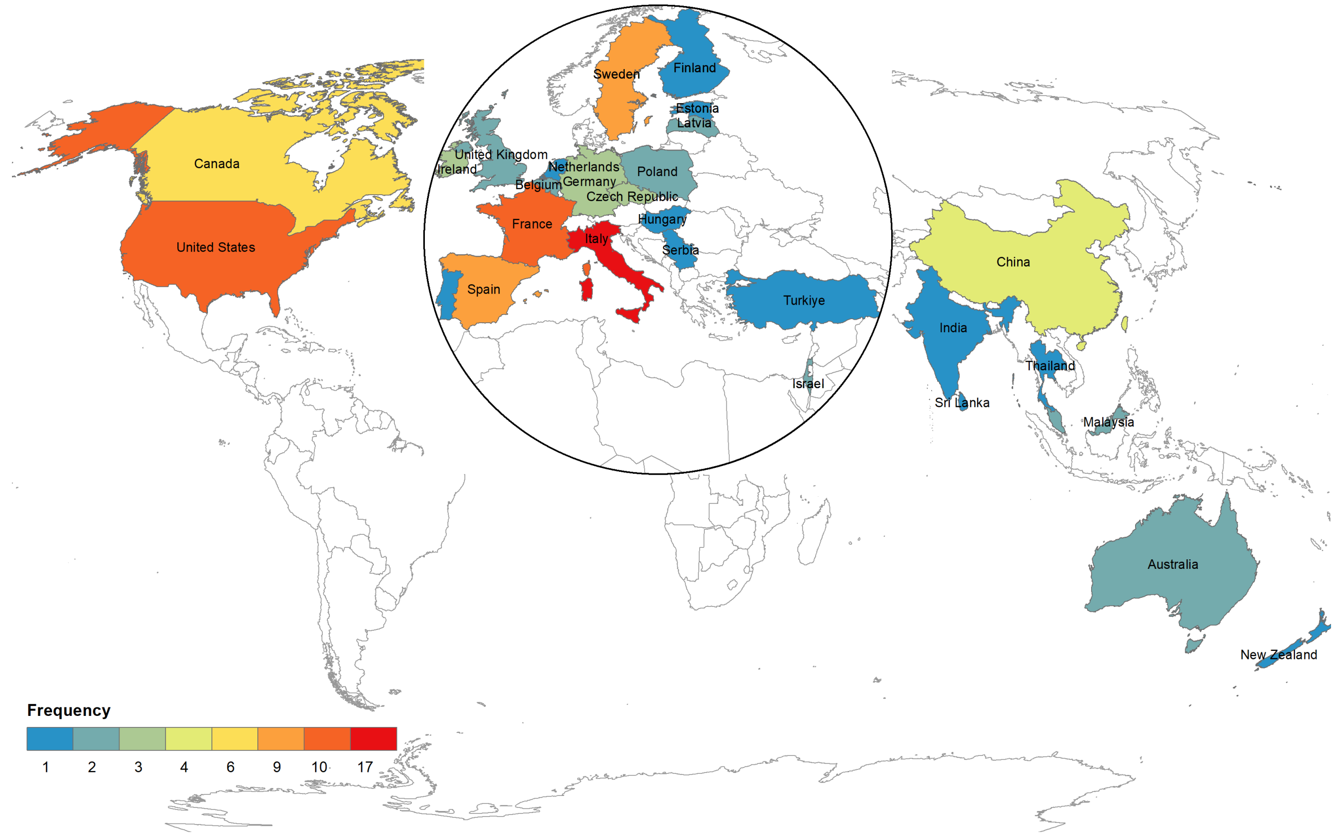

FIGURE 5 Map of the world showing the number of publications by countries.

classification framework (see Figure 9): LCA (n=40), VC (n=30) and feasibility analysis (n=28). Collectively, the thematic content of VC articles was found to be product unspecific or multi-product, while the LCA and feasibility articles dealt with specific hemp products. Notably, only two articles, one each under the LCA and feasibility analysis categories, were related to "Phytoremediation," indicating that very few articles built upon the narrative of industrial hemp performing well under marginal land conditions.

3.2.1 | Life cycle analysis

Articles under the LCA category assessed the environmental burden of industrial hemp products, mostly considering cradle-to-gate boundaries across environmental indices. As shown in Annex 1, these included global warming potential, eutrophication, acidification, and ecotoxicity. Under the LCA category, hempcrete has been studied the most (20% or 50% of the total), followed by bio-composites (7) with four articles belonging to pulp and three articles related to solid/biofuels, three for fibers, one each related to phytoremediation, hemp oil and green protein respectively. The five hempcrete and three bio-composite related articles co-studied LCC, which estimates costs incurred by actors of respective (product) VCs. In all, LCA has been the most comprehensively studied among the three deductive categories. As such, consideration of a wide range of close comparators, distinct boundaries, and units of analysis have attributed to the analytical rigor of LCA studies (Annexes 2 and 3).

3.2.2 | VC analysis

Under the VC category, the 10 initial articles studied economic VC actors and their roles within the chain. In other articles from the most recent decade, eight identified critical intervention areas and explored intervening techniques, while nine articles simultaneously recognized the value-adding opportunities to convert raw hemp components into high-value products. Two articles studied the prospects of novel blockchain technology to solve issues in the hemp VC. Finally, one article explored competitive hemp products for marginal land through multiple European nations' stakeholders' social-VCA.

3.2.3 | Feasibility analysis

Industrial hemp as an energy crop for producing biofuels (bioethanol, biodiesel, and methane) and solid biofuels

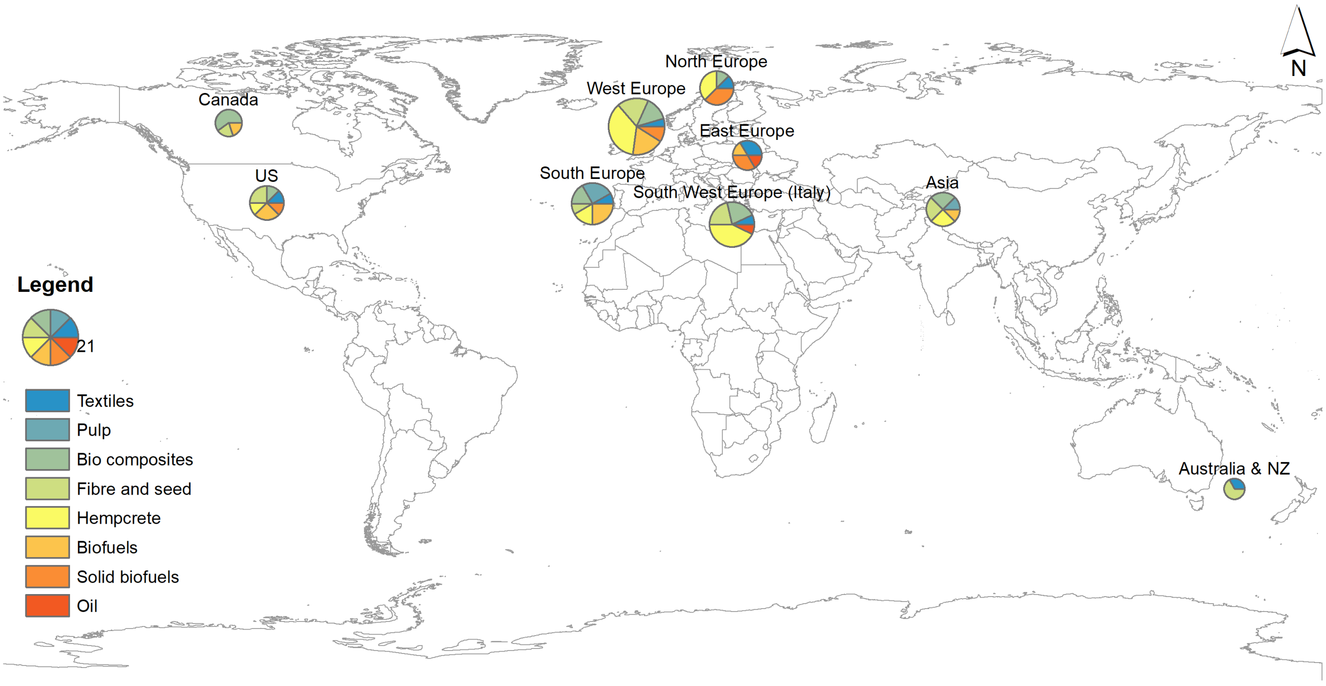

FIGURE 6 Map of the world showing regional distribution of hemp products as emphasized by the selected articles' country of origin.

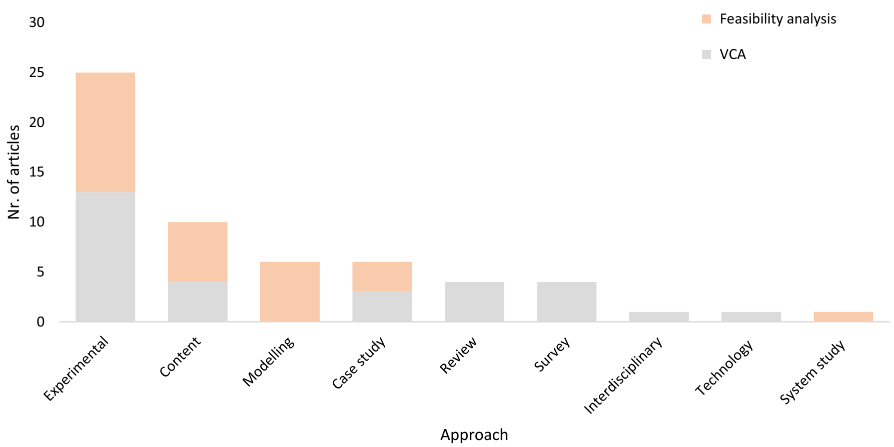

FIGURE 7 Approach-wise distribution of articles.

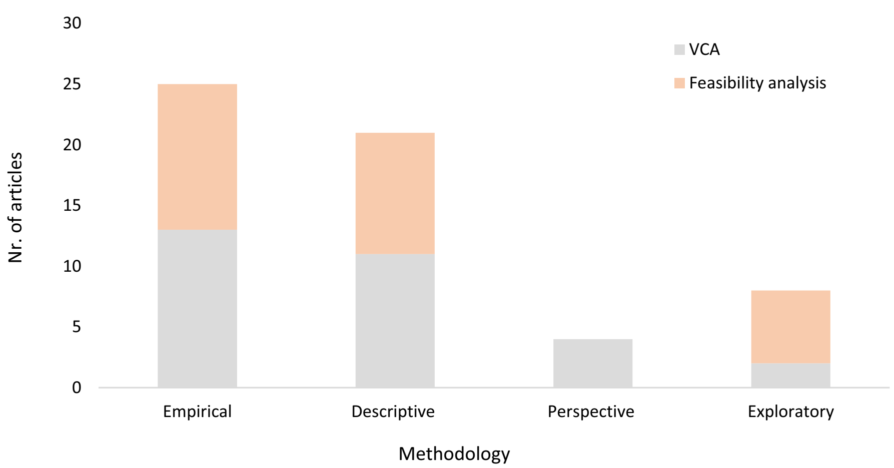

FIGURE 8 Methodology-wise distribution of articles.

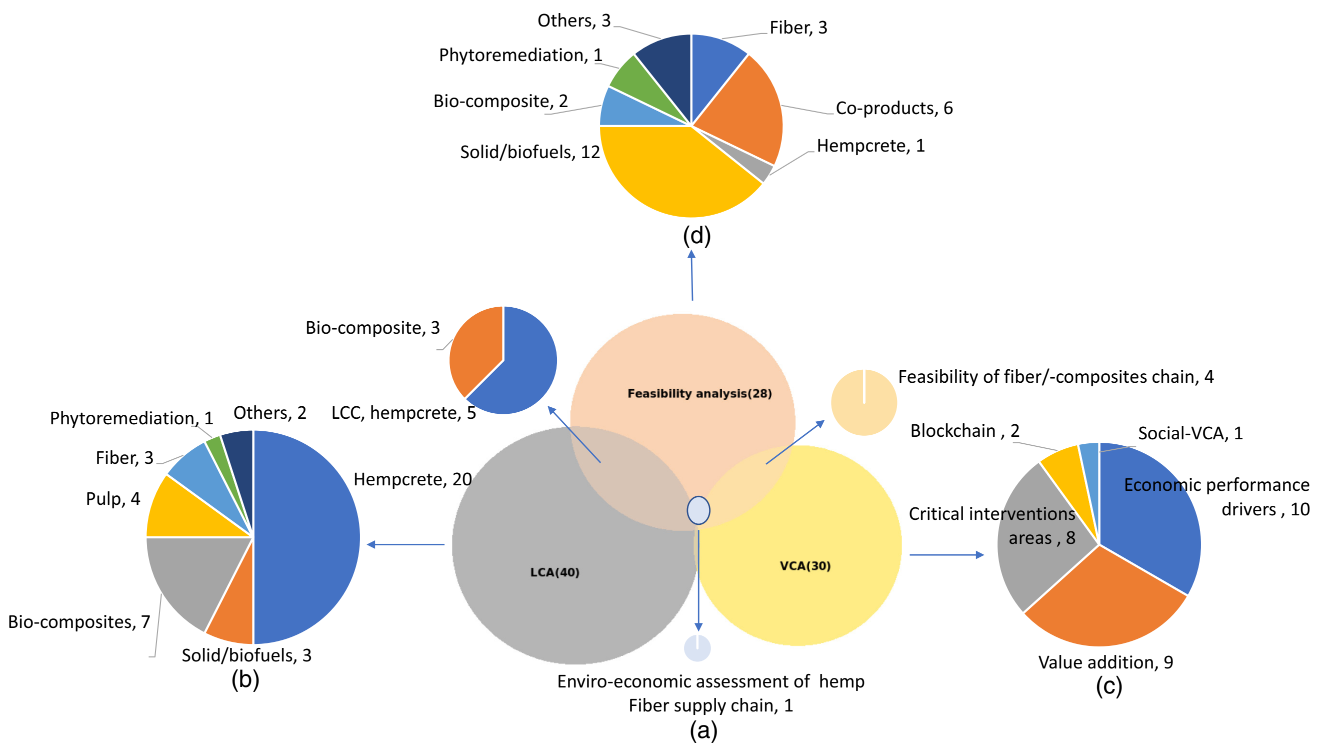

FIGURE 9 Emerging themes of included research articles. The center bubbles (a) indicate broad (deductive) categories and three pie charts around the bubbles show the number of articles with inductively derived themes across each category. (b, d) corresponding to the respective LCA and feasibility bubbles show product-specific themes, while (c) which corresponds to VCA contains themes related to different VC dynamics. The numerals indicate number of articles. $N > 98$ due to overlapping themes.

(briquettes and pellets) were the most extensively studied products under the feasibility analysis category ($n=13$). Next, concurrent products (i.e., fibers and biofuel, and fiber and seed) ($n=6$), fiber ($n=3$), bio-composites ($n=2$), phytoremediation ($n=1$) and hempcrete ($n=1$), and two others (hemp oil and seed) were prioritized hemp products studied from a feasibility perspective. Half of the studies undertaking feasibility analysis solely considered the "cost" of industrial hemp products from manufacturers and the user perspective, while the other half studied factors like benefits and profit margins. This leaves a gap in literature regarding the profitability of some hemp products.

Finally, one of the articles encompassed all three categories, comparing GHG emission and economic feasibility (yield/cost/price) from industrial hemp tailored to bioenergy production, against those of wheat and poplar.

4 | DISCUSSION

4.1 | Revisiting the bibliometric overview

The spatiotemporal trend of selected articles reveals that over 90% of studies that consider the enviro-economic and feasibility assessments of industrial hemp are conducted in Europe or North America. More than half of them were published in the past 5 years. This can be attributed to the recent lenient and lucid EU regulations for industrial hemp (Sorrentino, 2021), which has enabled an environment for conducting research. The surge of US interest in hemp research followed the authorization of the Farm Bill 2018 that also led to a substantial rise in publications (Abernethy, 2019). Moreover, the increasing interest in the topic of the environmental and economic sustainability of industrial hemp among scholars of the Western world can be explained by the EC's extended commitment toward the circular economy 2015 (EC, 2024). This envisages and encourages a harmony between economic development and environmental protection (Domenech & Bahn-Walkowiak, 2019). However, there is a clear dearth of research on industrial hemp in related facets in other parts such as vast areas of the Global South.

Hemp products prioritized by the studies tended to have regional prioritization. In general, hempcrete with environmental amicability was the most highly sought product in the European research papers. Indeed, the use of hempcrete for insulation purposes is one of its main applications in Europe (Carus & Sarmento, 2016). Of particular significance, our results emphasize regional specificity, with papers from Southern European countries (i.e., Spain and Portugal) mostly highlighting hemp-for-pulp and East European countries favoring textile fibers. The specific product focus across these country-specific studies can be explained by regional factor; for instances, the Spanish climate that limit the application of industrial hemp to only pulp paper and the East European condition suitable for textile quality yarn production (Gorchs & Lloveras, 2003).

4.2 | Environmental assessment of industrial hemp

The selected 40 articles conducted LCAs of major hemp products with main focus on the global ecological index such as carbon emissions (CO_2) associated with global warming, as well as local/regional eutrophication and acidification indices. Some of the identified carbon hotspot are the yarn production phase during textile manufacturing (Turunen & Van Der Werf, 2007), the functionalization phase for use as composite fiber, and use of lime binder during hempcrete formation (Pretot et al., 2014). However, hempcrete related emissions are counterbalanced to carbon-negative values because of photosynthetic CO_2 fixation during the growth phase and CO_2 absorption (via. carbonation) during the use phase (Arehart et al., 2020). Estimated net carbon storage potential of (m^2) unit hempcrete insulation wall (of varying thickness) ranges from 4.28 kg CO_2 eq (Zampori et al., 2013) to 36.08 kg CO_2 eq (Ip & Miller, 2012). Shortening the supply chain phase of resource extraction (Di Capua et al., 2021) and the use of unfired binders alternatives (Florentin et al., 2017) instead of lime binder (Pretot et al., 2014) can further reduce hempcrete-associated emissions.

The application of (nitrogenous) fertilizer and pesticides during cultivation of industrial hemp has been the subject of ecological concern, leading to regional consequences such as eutrophication, (Bernas et al., 2021), acidification (Casas, 2005), and ecotoxicity (Seile et al., 2022). Owing to these environmental constraints on input use, hemp as a pulp for paper remains less sustainable than flax (González-García, Hospido, et al., 2010; González-García, Teresa Moreira, et al., 2010), eucalyptus (Da Silva Vieira et al., 2010), and woody perennials (Sun et al., 2018). Regarding the ecological footprint associated with hemp hurds derived biofuels (e.g. bioethanol), the pros of reduced fossil fuel demand and photooxidation (González-García, Moreira, et al., 2010) can be counterbalanced by reallocating the environmental burdens of by-products such as glycerine, cakes, and straw. Other energy crops like triticale, wheat, sugar beet, and maize were considered more carbon and energy-efficient than hemp for biofuels, as illustrated by Börjesson et al. (2015).

Moreover, above discussions are based on the research findings of industrial hemp grown in the dedicated agricultural land under input intensive production system. The performance of industrial hemp with minimal inputs and in marginal landscapes could be a good discussion topic in future studies. To this end, a pioneering study by Todde et al. (2022) showed the relative energy saving of 36.8 GJ and emission reduction by 641 CO_2 eq/ha from industrial hemp under contaminated soil and a low-input scenario, when tailored to bioenergy production. More empirical studies are needed to widen our understanding of how hemp will perform and what hemp products can be produced with low environmental trade-offs, under given unconducive scenarios in particular regions.

4.3 | VCA of industrial hemp

Based on the analysis of included VC articles, the stakeholder rendezvous at the Canada AgFibe 2002 conference can be considered a significant milestone for industrial hemp VC studies. Back then, the linkage between VC actors (e.g., producers, processors, and buyers) in the fiber supply chain was critical in the Canadian fiber VC (Hanks, 2003). The French system also demonstrated how linkages between VC actors were crucial (Alex et al., 2005). The study recognized the need of network consortium among farmers and primary processors to ensure the continuous supply of high-quality textile fibers. Over the course of time, expanding industrial applications demanded increasingly economical production of high-quality diversified raw material components, including fiber, hurds, and seed. Consequently, the thematic focus of the most recent decade on VC research shifted towards the identification and workings of technical or production process-oriented issues, with a strong focus on extracting raw materials for market competitive diverse hemp products in more economical ways.

4.4 | Potential areas for improving economic performance

In general, hemp harvesting (Pari et al., 2015) and fiber processing (Vandepitte et al., 2020) have been identified as key intervention areas for global hemp VC development (Müssig et al., 2020). Due to a slow harvesting and components extraction process, the traditional manual hemp harvesting method is no longer feasible, especially in parts of the industrialized world with expensive labor charges. So, these exigent circumstances drive the need for mechanization. Various researchers have conducted trials using currently available harvesters. For instance, Vandepitte et al. (2020) adapted agronomic practices to acquire the desired size of hemp stalks that fit within the arc of automated flax harvesters. Meanwhile, Assirelli et al. (2020) reduced the rotary cutter of self-propelled forage harvesters to separate fibers right from standing. These harvesting techniques excelled in speed of operation alongside reduced labor with enhanced quality of component fiber (tow and long fibers) and shives yields. The sunflower head assembled combined harvester is one recently tested technique that enables the acquisition of valuable threshing residues during seed harvesting (Assirelli et al., 2022).

At the fiber processing stage, decortication (Gratton & Chen, 2004) and spinning steps (Zimniewska, 2022) have been a recurring concern (Wang et al., 2018). Fibernova D7 type decorticator was proposed previously, but with high moisture retention (70.5%) in hurds, it is economically unviable at the farmers' level (Riddlestone et al., 2006). Similarly, a linen spinning technology can be adjusted for hemp yarn production, but this system demands a specialized implementation configuration that is inaccessible in most markets (Zimniewska, 2022). Other identified issues in the hemp VC include funding sources and traceability, with one potential solution being the proposed adoption of novel blockchain technology (Ferrández-Pastor et al., 2022; Liu et al., 2023).

4.5 | Value addition

Researchers have explored various opportunities within the industrial hemp VC that showcase ways to add value to the products. For example, the blend of hemp fibers during composite knitting step can create UV-resistant high-value apparels (Kocić et al., 2019; Müssig et al., 2020). Similarly, hemp seed is valued for human food fortification, to both enhance protein content and stabilize the physico-bio-chemical properties of food products (Burton et al., 2022).

Valorization is one such technique that can convert low-value biomass into value-added bioproducts and chemicals (Loow et al., 2016). Moreover, various biophysical pretreatment and accompanying recovery procedures (Murthy & Madhava Naidu, 2012) have been the basis of several experiments (Figure 10) to produce high-value commercial products with a range of applications. Hemp hurd, a by-product of the textile industry (Dang & Nguyen, 2006), can be valorized into textile fibers and nanocellulose through a route called Organosolv pulping (Muangmeesri et al., 2021). Sonication–microwave–alkali treatment procedure is another way to convert fibers into nanocrystalline cellulose suitable for bio-composite reinforcement (Xu et al., 2013). Similarly, volatile fatty acids (e.g., single-cell proteins and polyhydroxy butyrates) are high-end market products obtained through the acidogenic fermentation of hurds, leaves, and inflorescence (Moscariello et al., 2022). Furthermore, mercerization and subsequent enzymatic treatment (George et al., 2015) or tall oil application (George et al., 2016) are demonstratable techniques for removing the hydrophilic hemicellulose content of hemp fibers to enhance its thermal properties. Capitalising on valorization opportunities will enhance the economic value of industrial hemp products. The development and scaling-up of laboratory-demonstrated techniques to an industrial level will ensure extra income generation.

4.6 | Economic feasibility of hemp-based products

Hemp as a feedstock for bioenergy generation entailing biofuels (e.g., bioethanol, biodiesel, and biogas), briquettes, and pellets were the most studied products among articles included under the feasibility analysis category. However, industrial hemp for bioenergy production in Northern Europe did not look economically sanguine under the current levels of feedstock productivity, input cost, and energy price. In the Irish context, Rice (2008) calculated a negative gross margin of energy hemp at the prevailing energy price of US$4.06/Gj (peat as fuel). Highly optimistic scenarios including 14 t/ha DM yield, organic fertilizer input, and start-up grant availability may provide a profit margin of US$1123/ha (Finnan & Styles, 2013). But the maximum yield potential of European hemp cultivars' is 10.7 t/ha (Kolarikova et al., 2015). In Estonia, financially remunerative hemp briquette necessitated a surge in price from 130.63 US$/t to at least 199.47 US$/t (Alaru et al., 2013). The prospect of hemp pellets production is also disarming, with an estimated input (tillage and seed fertilizer) cost of 432 US$/t DM, which is at least 52.9 US$/t DM higher than other energy crops like reed canary grass and other crop by-products such as shavings and straw (Nilsson et al., 2011). Additionally, methane production from hemp biomass in Europe is not fortuitous (Gissén et al., 2014). The estimated hemp feedstock yield of 80 Gj methane/hac is only half of sugar beet (including tops) yield and, with a feedstock production cost of 15.12 US$/Gj, profit realization cannot be expected.

Nonetheless, due to a relatively low-input demand and high productivity, the use of hemp fibers can be more cost-effective than cotton for textile industries (Duque Schumacher et al., 2020). Similarly, the application of hemp fiber composites such as in automobiles (Hagnell et al., 2020), in bioplastic production (La Rosa et al., 2013), and in manufacturing conduits and fittings (Haylock & Rosentrater, 2018) have shown considerable cost reductions when compared to petrochemical-derived glass

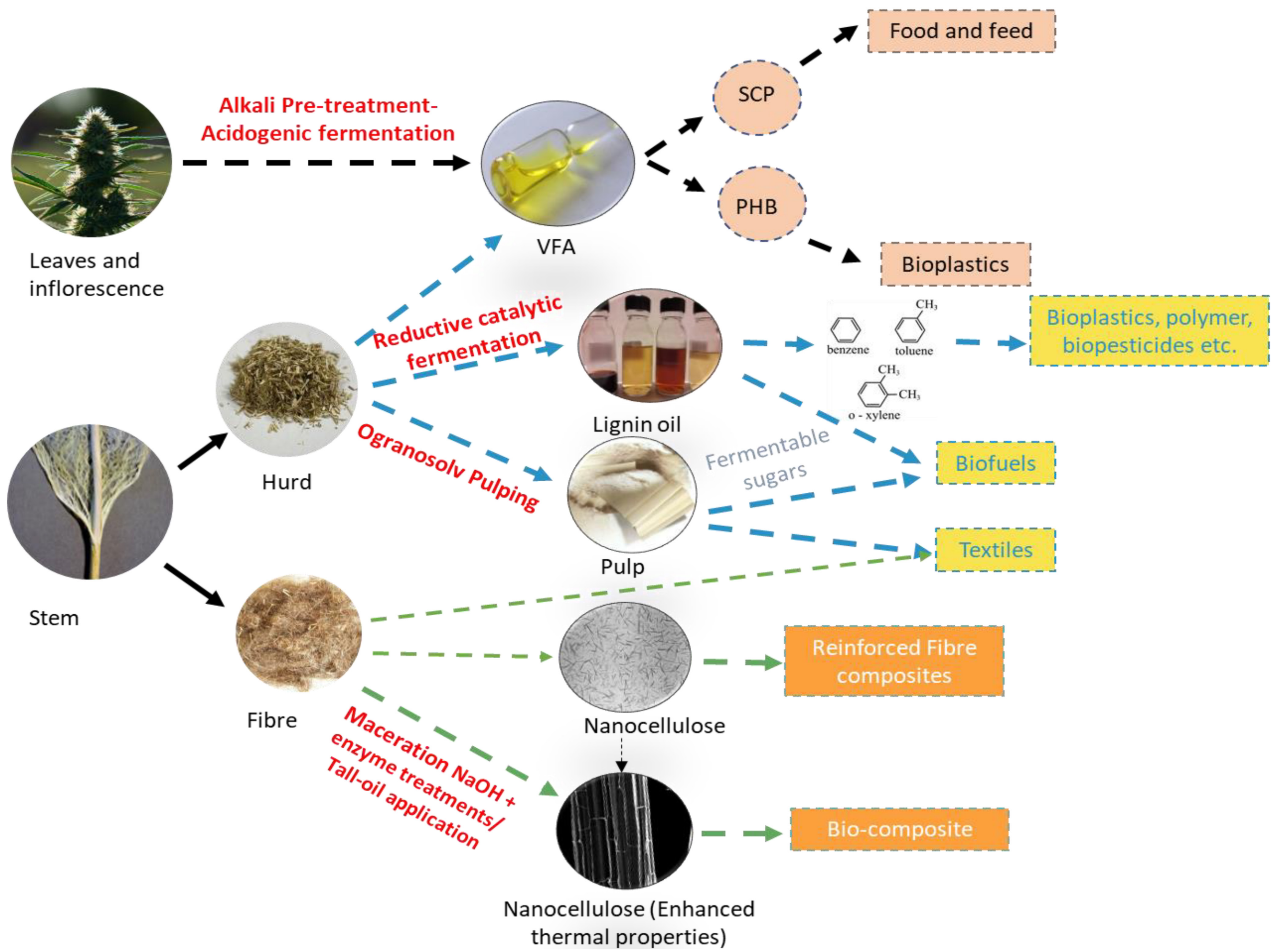

FIGURE 10 Illustration of different routes of valorization proposed by different authors.

fiber and non-renewable talc. However, bio-composites sourced from flax fiber and date palms were cheaper than hemp bio-composites for the automobile industries (Al-Oqla et al., 2015).

The cost competitiveness of hempcrete for housing insulation can vary with region. In Italy, Annibaldi et al. (2020) estimated installation costs for the inner surface (wall) was 22.88 US\$/m^2, which was 24.24 US\$/m^2 cheaper than alternative insulation materials like aerogel, cork, calcium silicate, and polystyrene. It also had a low life cycle NPV costing (3024.9 US\$/m^3) compared to either synthetic polyurethane (3217.34 US\$/m^3) and mineral rock wool (3122.5 US\$/m^3; Rocchi et al., 2018). In France, insulation solutions like glass wool, cellulose fiber, rigid foam polyurethane expanded-polystyrene (XPS), and extruded-polystyrene (EPS) were more economical (Colli et al., 2020). Moreover, the economic viability of hemp fibers for various applications depends on the cost-effective acquisition of fiber material, influenced by fluctuations in the fiber process (Seile et al., 2022). In fact, high cultivation (particularly N fertilization) and manufacturing costs has led to relative cost inefficiencies at the upstream level as compared to alternative bio-based solutions such as miscanthus (Schulte et al., 2021). From the producer's perspective, high input costs may infer low relative profitability, regardless of the ultimate use.

4.6.1 | Co-production scheme

Profitability of industrial hemp can be assured through a production scheme that considers multiple co-products. Figure 11 presents pooled data indicating positive returns from bioethanol and grain co-products, with a range of 640 US\$/ha to 2632 US\$/ha across hemp varieties and geographical location, while there is a profit loss under a bioethanol-only production scheme. This was observed directly in several regional localities. For example, a dual production scheme of fiber and seed in Turkey (Ceyhan et al., 2022) or a combination of concurrent products of biodiesel, fiber, or seed in Malaysia (Szulczyk & Badeeb, 2022), were seen as profitable. However, hemp fiber production only in

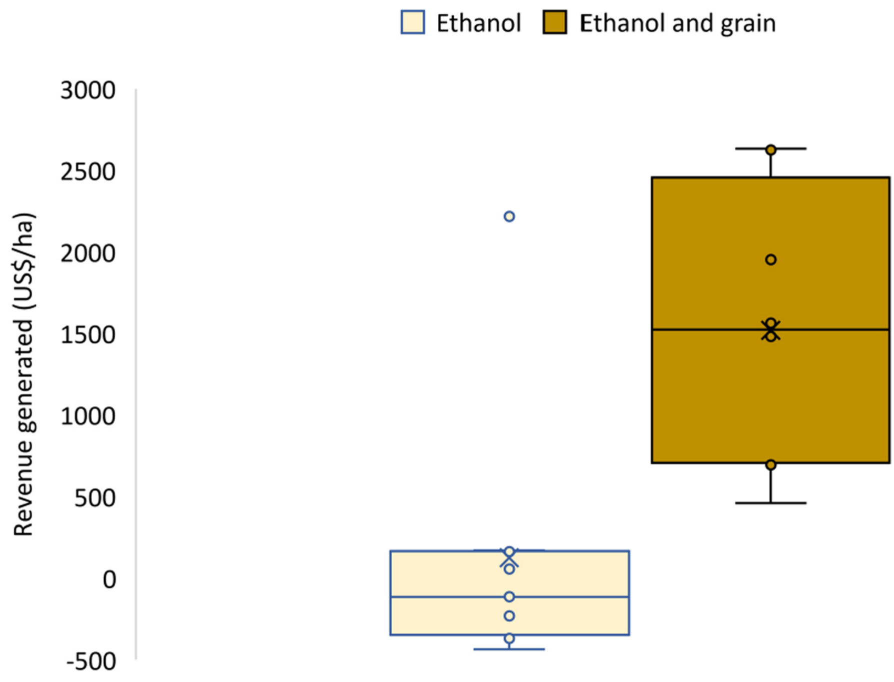

FIGURE 11 Comparison between revenue generation from ethanol and co-product ethanol and grain. Based on the pooled revenue figures of different nations estimated by Parvez et al. (2021), Das et al. (2017, 2020) and Buck and Senn (2016).

both the Turkish (Ceyhan et al., 2022) and the Malaysian edapho-climatic scenarios (Wimalasiri et al., 2021, 2022) resulted in a monetary loss of −555 US$/ha and −2000 US$/ha to −1800 US$/ha, respectively. Other findings indicate that in a co-production scheme profitability could be further enhanced through biotechnological advancements that increase the amount of products with highest price, such as increasing hemp plant lipid content to enhance high-priced biodiesel production processes over ethanol production (Viswanathan et al., 2021).

The current body of evidence suggests positive returns on concurrent hemp products. However, hemp as a dedicated crop in the arable landscape should also be financially competitive with other conventional crops. Future studies should therefore investigate the relative profitability of industrial hemp as compared to established arable crops. Furthermore, current findings are region-specific, with most observed in developed nations and cannot be generalized to other parts of the world. The Global South, for example, is home to the vast majority of smallholder farmers, who are characterized by low-input farming systems and cheap labor forces (La Rosa & Grammatikos, 2019). These regions can potentially host more economically viable industrial hemp production systems; however, countries in the Global South producing industrial hemp from this aspect are yet to be studied.

4.7 | Enviro-economic linkages

Overall, it may be surmised that the arable landscape of the Global North cannot have environmentally sustainable industrial hemp vis-à-vis profitability. To illustrate this, in France, Institut Technique du Chanvre (2007) recommended a nitrogen (N) fertilizer rate of 120 kg/ha (Abernethy, 2019) for achieving optimum economic returns from industrial hemp (Alaru et al., 2013). Thus, the environmental consequences of field nitrogen application are evident. A study by Finnan and Styles (2013) suggested that organic fertilizers such as low or no-cost sludge applications are both environmentally friendly and economical, and therefore make profitable yield alternatives. However, their findings indicated lucrative hemp biomass yield from organically grown hemp is more likely case or context sensitive and cannot be generalized. Rather, a premium price received by the producers for delivering eco-friendly (organic) products can be a key profitability factor. Therefore, understanding consumers' perceptions toward hemp bioproducts and their willingness to pay premium prices should drive future research. Additionally, the price competitiveness of all the economic actors involved in the industrial hemp VC could be another important aspect for further analysis. For this, a feasibility study should be conducted from the vantage of the VC, aiming to quantify the monetary flow across all the actors along the entire chain.

5 | CONCLUSION

To recapitulate the major findings of our bibliometric analysis, above 90% of the studies were conducted in the regions of Europe and North America. The results revealed regionally prioritized hemp products, such as hempcrete in Southwest Europe (Italy), biofuel in Northern European states, and textile fiber and bio-composites in Eastern Europe, Asia, and North America. These findings emphasize the large concentration of studies on hemp products in the Global North, with insights from the Global South remaining uncaptured.

LCA studies show that industrial hemp can provide environmentally benign products for transportation to the construction sectors as compared to fossil fuel alternatives. In particular, hempcrete is an equivocally touted climate-friendly construction solution, with net carbon storage from at least 4.28 CO_2 eq/m^2 to 36.08 kg CO_2 eq/m^2 due to carbon assimilation during growth phase and carbon absorption during use phase. However, alternative bio-based solutions from flax, palm, or eucalyptus can be more ecologically amicable. Moreover, the application of fertilizers and pesticides during the biomass production stage of industrial hemp can incur an environmental risk.

The most recent decade on VC research recognized the urgent need for mechanization at both the harvesting and fiber processing nodes within the chain. This can reduce manual labor costs and enable the acquisition of plant components of various application. Research also divulged value-adding steps and valorization pathways from laboratory experiments to convert hemp residual biomass into high-value products such as VFAs and nanocellulose. To monetize these valorized products effectively, future studies should focus on scaling at the industrial level.

The research outcomes in the feasibility analysis category show that co-production schemes in combinations, like biofuel and grain or fiber and grain, are financially remunerative, while sole production schemes for biofuels (pellets and briquettes) and fiber remain unfeasible. The feasibility of bio-composites and hempcrete are elusive since most literature to date investigates the cost effectiveness of industrial hemp at the upstream user level and the price competitiveness at the downstream producers or manufacturer level is still largely unknown.

AUTHOR CONTRIBUTIONS

Rajan Budhathoki: Conceptualization; data curation; formal analysis; methodology; writing – original draft. **Tek Maraseni:** Conceptualization; supervision; writing – review and editing. **Armando Apan:** Supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

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 STATEMENT

Data will be made available upon request.

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ANNEX 1 Summary of LCA of different hemp products, methodology, unit of analysis, span, and considered environmental indicators.

			LCA methodology				Considered (major) environmental impacts								
Reference	Products	Country	Study approach	Comparators	Unit	Span (years)	GW	E	A	T	OD	FD	PM	LU	O
	Direct plant products														
Van Der Werf (2004)	Fiber	France	Cradle-to-farm gate	Fiber hemp versus arable crops			×	×	×	×				×	×
Turunen and Van Der Werf (2007)	Fiber	Hungary	Seeding-to-spinning of yarn	Fiber hemp versus Flax fiber across different rating scenarios	100 kg yarn		×	×	×			×		×	×
Bernas et al. (2021)	Edible oil	Czech Republic	Cradle-to-gate	Hemp oil versus traditional oilseed crops	1 m^3 edible oil and parcel of land required for this production volume	-	×	×	×	×		×			
Campiglia et al. (2020)	Seed	Italy	Cradle-to-gate	Different hemp genotypes	1 kg seed		×	×	×	×	×	×	×	×	×
	Fiber composites														
Recupido et al. (2023)		Italy	Cradle-to-gate (factory)	Among different types of hemp-based fillers	5.9 gm filler	—	×	×	×	×	×	×			×
Seile et al. (2022)		Latvia	Cradle-to-gate (factory)	Among hemp/— and flax/PLA and between non-renewable polyamide composite	1000 × 500 mm dimension composite	—	×	×	×	×	×	×			
Ead et al. (2021)															
Haylock and Rosentrater (2018)		US	Cradle-to-grave	Hemp fiber (PLA composite) filler versus other renewable non-renewable fillers	10, 100 and 1000 gm fillers		×	×	×	×	×				×
La Rosa et al. (2014)		Italy	Cradle-to-gate (factory)	Sandwich panel manufactured with hemp/ bio-epoxy resin versus conventional epoxy/glass fiber	0.4 × 0.4 × 0.02 m dimension sandwich panel	—	×	×	×	×	×	×			×
Ramesh et al. (2022)		India	—	Review	—	—	×	×	×	×	×	×			×
	Building materials														
Haik et al. (2023)	Hempcrete	Israel	Attributional or consequential	Lime hempcrete versus hempcrete with unfired binders as a substitute	1-storey building	50	×								
Mouton et al. (2023)		Belgium	Cradle-to-grave	Bio-based dwelling components	1 m^2 of purposed building elements	60	×						×	×	
Vilaboa Díaz et al. (2022)		Portugal	—	Materials from agricultural waste	1 kg of bio-based materials		×								
Colli et al. (2020)		France		Hempcrete versus bio-based and synthetic insulation solutions	1 m^2 of insulating materials		×			×		×	×		
Ip and Miller (2012)		UK	Attributional	Exploratory study	1 m^2, 0.3 m thick hempcrete wall	100	×								
Di Capua et al. (2021)		Italy	Cradle-to-gate	Hempcrete vs conventional construction materials	1 m^3 wall	-	×			×		×			

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ANNEX 1 (Contiuned)

Reference	Products	Country	LCA methodology: Study approach	Comparators	Unit	Span (years)	Considered (major) environmental impacts: GW	E	A	T	OD	FD	PM	LU	O
Pittau et al. (2020)		Italy		Hempcrete blocks as a surface insulator versus another insulation choice with refurbishment and reconstruction case	Historical industrial building		×	×	×	×	×	×	×	×	×
Scrucca et al. (2020)		France	Cradle-to-gate	Exploratory study (hurds for building sector)	1 kg hemp hurds		×					×			
Arehart et al. (2020)		US	Cradle-to-gate	Exploratory study (hempcrete for insulation material)	1 m^2 wall		×	×							
Heidari et al. (2019)		France	—	Treated hemp hurd versus untreated hurd and reference wall materials	1 kg hemp hurd and sol–gel (coating)/1 m^2 insulation wall	60–120			×	×				×	×
Sinka et al. (2018)		Latvia	Cradle-to-gate	Lime hempcrete versus hempcrete with magnesium binder as lime substitute	1 m^2 wall		×	×	×	×	×				×
Mungkung et al. (2016)		Thailand	Cradle-to-gate	Hempstone versus artificial stone	Hempstone sheet (3.04 L × 0.82B × 0.012H m^3)		×	×		×					
Pretot et al. (2014)		France	Cradle -to-grave	Hempcrete walls with different coating compositions	1 m^2 hempcrete wall having 27 cm thickness (incl. 2 cm and 1 cm external and internal coating)	100	×	×	×		×	×			×
Hult and Karlsmo (2022)	Insulation	Sweden	—	Hemp fiber versus conventional insulation solution	Nuclear family home	50	×								
Dickson and Pavía (2021)		Ireland	—	Hemp versus conventional insulation	1 m^2 insulation materials		×	×	×		×	×			×
Schulte et al. (2021)		Germany	Cradle -to-grave	Among materials of biological (incl. hemp) origin and between non-renewables	1 m^2 external wall	70	×	×	×	×	×	×	×	×	×
Florentin et al. (2017)		Israel		Hemp-lime insulation versus conventional insulation solution	110 m^2 Residential building apartment	50	×								
Zampori et al. (2013)		Italy	Cradle-to-gate	Hemp fiber insulation versus rockwool insulation	1 m^2 insulation panel	—	×		×	×	×	×		×	×
Rocchi et al. (2018)		Italy		Among renewables (hemp and kenaf) and between non-renewables	1 m^2 insulation panel	25	×				×				×
Kiesse et al. (2017)		Germany		Environmental impacts resulting from various potential actions	1 m^2 insulation panel and wall	50/100	×	×	×	×					×
	Pulp and paper														
González-García, Hospido, et al. (2010)		Spain	Cradle-to-gate	Hemp versus flax fiber	1-ton fiber	—	×	×	×			×			×

ANNEX 1 (Contiuned)

			LCA methodology				Considered (major) environmental impacts								
Reference	Products	Country	Study approach	Comparators	Unit	Span (years)	GW	E	A	T	OD	FD	PM	LU	O
González-García, Teresa Moreira, et al. (2010)		Spain	Cradle-to-gate	Hemp versus flax fiber			×	×	×	×					×
Da Silva Vieira et al. (2010)		Portugal	Cradle-to-pulp	Hemp versus eucalyptus paper	1-ton paper manufactured	-	×	×	×					×	
Sun et al. (2018)		China	Cradle-to-gate	Hemp and flax pulping versus straw-based pulping	1 ton of wheat straw pulp	—	×	×	×	×	×	×			×
	Bioenergy														
González-García, Moreira, et al. (2010)	Ethanol	Spain	—	Hemp hurd feedstock versus alternative lignocellulosic feedstocks	1 km distance travelled by flexi fuel vehicle	—	×	×	×			×			×
González-García et al. (2012)		Spain	—	Hemp hurd feedstock-based bioethanol at varying blends	1 km distance travelled by flexi fuel vehicle	—	×	×	×			×			×
Börjesson et al. (2015)	Methane	Sweden	Field to tank	Biogas production from hemp versus different crop biomass	1 GJ of biogas produced		×								
Todde et al. (2022)	Electricity	Italy	Cradle-grave	Electricity generation using hemp biomass versus traditional sources	1 kg dry biomass and 1 ha phytoremediation area										
Casas (2005)	Biodiesel	Spain	Cultivation to fuel manufacturing	Biodiesel versus diesel			×	×	×		×	×			×

Abbreviations: A, acidification; E, eutrophication; FFD, fossil fuel depletion; GW, global warming potential; LU, land use; O, others; OD, ozone depletion; PM, particulate matter; T, toxicity.

ANNEX 2 Summary of the studies on value chain analysis of industrial hemp, approach, methodology used, their applications, and country.

References	Objective	Approach	Methodology	Application/ products	Country
Liu et al. (2023)	To study the applicability of blockchain technology in supply chain management	Content	Descriptive	Unspecific	China
Moscariello et al. (2022)	Investigating valorization procedure on hemp biomass to achieve high-value bioproducts	Experimental	Empirical	Multipurpose (unspecific)	Italy
Ceyhan et al. (2022)	To conduct a value chain analysis of industrial hemp from an economic perspective in Turkey	Survey	Descriptive	Fibers and seed	Turkey
Ferrández-Pastor et al. (2022)	To suggest a model that parallelly integrates experts' knowledge and technology, that is, blockchain and internet of things approach for enhancing traceability of industrial hemp chain	Content	Descriptive	Unspecific	Spain
Burton et al. (2022)	To review the studies about the applicability of hemp seed as a value-added human dietary ingredient	Review	Descriptive	Seed	Australia
Zimniewska (2022)	To review literature on fiber properties and processing identifying their intervention nodes	Review	Descriptive	Textile	Poland
Assirelli et al. (2022)	To investigate a novel hemp seed supply chain through manipulation of sowing time and harvesting practices	Experimental	Empirical	Propagating seed	Italy
Panoutsou et al. (2022)	To conduct social perspective VCA of industrial hemp in marginal agricultural land	Survey	Descriptive	Unspecific	Europe
Zhao et al. (2021)	SWOT analysis of industrial hemp among different regions of China	Survey	Perspective	Unspecific	China
Muangmeesri et al. (2021)	To demonstrate the valorization techniques converting low-value hemp stalks into high-value compounds	Experimental	Empirical	Multipurpose (unspecific)	Sweden
Vandepitte et al. (2020)	To evaluate the fiber characteristics of hemp varieties and their feasibility to get processed into flex scutching line	Experimental	Empirical	Textile	Belgium
Rupasinghe et al. (2020)	To provide an analytical review of industrial hemp about its potential usage as a value-added dietary ingredient and physical well-being	Review	Descriptive	Seed and seed oil	US
Colombo et al. (2020)	Value chain analysis of organically grown hemp for oil purposes in Sicily, Italy	Case study	Exploratory	Seed oil	Italy
Assirelli et al. (2020)	To evaluate the efficiency of a mechanical harvester in separating different hemp biomass components	Experimental	Empirical	Multipurpose (unspecific)	Italy
Giupponi et al. (2020)	To examine the Italian hemp production chain and overall usage	Survey	Descriptive	Multipurpose (unspecific)	Italy
Grégoire et al. (2020)	To investigate alternative fiber extraction processes and their effects on fiber morpho-mechanical characteristics	Experimental	Empirical	Geotextiles/ Bio-composite	France

ANNEX 2 (Contiuned)

References	Objective	Approach	Methodology	Application/ products	Country
Alonso-Montemayor et al. (2020)	To explore the fate of polyamide 6 in enhancing the mechanical strength of hemp fiber composites	Experimental	Exploratory	Bio-composite	Spain
Kocić et al. (2019)	To compare the properties of hemp fibers with other natural and synthetic fibers concerning UV protection	Experimental	Empirical	Textile	Serbia
Gusovius et al. (2019)	To compare the outcomes of various retting procedures enabling value-added chain and products	Experimental	Empirical	Bio-composite	Germany
Wang et al. (2018)	To compare the decortication efficacy of hemp varieties at a laboratory scale	Experimental	Empirical	Unspecific	Italy
George et al. (2016)	To analyze the effect of physical and enzymatic treatment on the physical and morphological properties of hemp	Experimental	Empirical	Bio-composite	Canada
Bono et al. (2015)	To explore areas for the development competitive industrial hemp value chain	Content	Perspective	Multipurpose (Unspecific)	France
Pari et al. (2015)	To provide a review on hemp (and other blast fibers) harvesting strategies adopted in China and Europe and to provide a way forward to enhance its product value	Review	Perspective	Multipurpose (Unspecific)	China
George et al. (2015)	To study the effect of physicochemical treatment on enhancing fiber for high-value application	Experimental	Empirical	Bio-composite	Canada
Xu et al. (2013)	To demonstrate the fate of enzymatic treatment in producing value-added products	Experimental	Empirical	Bio-composite	Canada
Garnier et al. (2007)	To analyze the marketing and economic forces within the French hemp chain	Content	Descriptive	Multipurpose (unspecific)	France
Riddlestone et al. (2006)	To evaluate a technology aimed at addressing a nodal point	Technology	Descriptive	Textile	UK and Australia
Alex et al. (2005)	To develop an economically resilient hemp value chain	Case study	Prescriptive	Textile	France
Hanks (2003)	To identify underlying problems of the hemp value chain	Case study	Descriptive	Textile	Canada
Amaducci (2003)	To develop a support system ensuring high-quality fibers	Interdisciplinary	Empirical	Textile	Italy

ANNEX 3 Summary of the studies on economic feasibility assessment of different hemp products, approach, methodology used, their applications, and country.

References	Approach	Methodology	Factor	Products	Application	Country
Wimalasiri et al. (2022), Wimalasiri et al. (2021)	Modeling	Descriptive	Profit (NPVB)	Fiber (and seed)	Unspecific	Malaysia
Duque Schumacher et al. (2020)	Content	Exploratory	Cost		Textile	US
Pecenka et al. (2009)	Content	Descriptive	Cost		Unspecific	Germany
Eerens (2003)	Content	Exploratory	Cost/benefit analysis		Unspecific	New Zealand
Salami et al. (2021)	Experimental	Empirical	Cost	VFAs	Agro-biochemicals, stimulants	Finland
Muneer et al. (2021)	Experimental	Empirical	Cost/benefit analysis	Green protein	Food and Feed	Sweden
Devi and Khanam (2019)	Experimental	Empirical	Cost	Oilseed	Edible Oil	India
Gorchs and Lloveras (2003)	Case study	Descriptive	Gross margin	Fiber	Paper	Spain
Seile et al. (2022)	Content	Descriptive	Price	Reinforced composite	Automotive	Latvia
Hagnell et al. (2020)	Case study	Descriptive	Cost		Automotive	Sweden
Haylock and Rosentrater (2018)	Modeling	Descriptive	Cost		Pipes and fittings	US
AL-Oqla et al. (2015)	Modeling	Descriptive	Ranking		Automotive	Malaysia
La Rosa et al. (2013)	Case study	Descriptive	LCC		Pipes and fittings	Italy
Schulte et al. (2021)	Content	Descriptive	LCC	Insulation materials	Building	Germany
Colli et al. (2020)	Case study	Descriptive	WLC (NPV)		Building (hempcrete)	France
Annibaldi et al. (2020)	Case study	Descriptive	Cost		Building (inner wall)	Italy
Rocchi et al. (2018)	Case study	Descriptive	LCC (NPV)		Building (roof)	Italy
				Bioenergy products		
Rheay et al. (2021)	Content	Descriptive	Cost	Bioenergy	Unspecific	US
Finnan and Styles (2013)	Experimental	Exploratory	Cost	Fuel	Unspecific	Ireland
Prade et al. (2012)	Experimental and modeling	Descriptive and exploratory	Economic efficiency	Fuel	Unspecific	Sweden
Dornburg et al. (2005)	Case study	Descriptive	Cost	Fuel	Unspecific	Poland and Netherland
Das et al. (2020)	Experimental	Empirical	Revenue	Ethanol (and co-products)		US
Das et al. (2017)	Experimental	Empirical	Revenue and cost	Ethanol (and co-products)		US
Buck and Senn (2016)	Experimental	Empirical	Revenue	Ethanol (and co-products)	Fuel (vehicles)	Germany
Szulczyk and Badeeb (2022)	Modeling	Empirical	Price			Malaysia
Viswanathan et al. (2021)	Modeling	Descriptive	Cost	Diesel	Fuel (vehicles)	US

ANNEX 3 (Contiuned)

References	Approach	Methodology	Factor	Products	Application	Country
Vávrová et al. (2022)	Experimental	Empirical	Cost	Briquettes and/or pellets		CZ
Kolarikova et al. (2015)	Experimental	Empirical	Cost/revenue/ profit			CZ
Gissén et al. (2014)	Experimental	Empirical	Cost	Methane	Heating	Sweden
Alaru et al. (2013)	Experimental	Empirical	Price			Estonia
Nilsson et al. (2011)	System study	Descriptive/ Exploratory	Cost		Heating	Sweden
Rice (2008)	Content	Descriptive/ Exploratory	Feasibility/ profitability	Biofuels	Heating/power generation	Ireland