

Cannabis Knowledge-to-Bioeconomy Nexus (CKBN): From Ethnobotany to Circular Innovation

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ABSTRACT

Cannabis sativa L. remains one of the most versatile plants at the interface of traditional medicine, modern pharmacology and industrial bioeconomy. In Pakistan—particularly the Himalayan foothills of Khyber Pakhtunkhwa (Swat, Dir, Chitral), Gilgit-Baltistan and adjacent valleys—the species retains deep ethnobotanical significance for pain, epilepsy, inflammation, respiratory complaints and cultural practice, while global research and markets expand around pharmaceutical cannabinoids and industrial hemp.

This review proposes the Cannabis Knowledge-to-Bioeconomy Nexus (CKBN): a sequential, indicator-driven framework that converts ethnobotanical knowledge into chemotypic characterisation, molecular-target mapping, biotechnological optimisation and circular bioeconomy outcomes. The framework is operationalised with a PRISMA-informed synthesis of peer-reviewed literature (Scopus, Web of Science, PubMed), bibliometric patterns (Bibliometrix/VOSviewer), cheminformatics (PubChem/LOTUS), network logic (Cytoscape/KEGG conventions) and spatial

reasoning for Pakistan using QGIS/ArcGIS principles.

Key findings: (i) traditional Himalayan and Pakistani indications for pain and epilepsy align with CB1/CB2 and non-canonical pharmacology of Δ^9 -THC and CBD; (ii) micropropagation protocols achieve 5–8 shoots per explant and >85 % ex-vitro survival under optimised conditions; (iii) industrial hemp shows documented phytoremediation capacity for Cd, Pb and Ni; (iv) the largest research gaps and highest innovation potential lie in metabolic engineering, field mycobiome–metabolite studies, waste valorization and comparative life-cycle assessment. CKBN therefore supplies both a conceptual scaffold and measurable priorities for research, breeding and policy in Pakistan and comparable mountain agro-ecosystems.

Keywords: Cannabis Sativa, CKBN; Pakistan; Ethnobotany; Khyber Pakhtunkhwa; Phytocannabinoids; Micropropagation; QGIS; Circular Bioeconomy

Introduction

Cannabis sativa L. (Cannabaceae) has been cultivated for fibre, seed and resin for at least six millennia (Ren *et al.*, 2021). Genomic and archaeobotanical evidence places early domestication in East Asia, with subsequent spread into the Himalayan foothills and the Indian subcontinent (Ren *et al.*, 2021; Zhang *et al.*, 2018). In the mountains of northern Pakistan—especially Swat, Dir, Chitral, parts of Gilgit-Baltistan and adjoining valleys—the plant remains embedded in local medicinal, cultural and sometimes agricultural practice (Mir *et al.*, 2021; Jan *et al.*, 2021; Bussmann *et al.*, 2021).

Contemporary ethnobotanical surveys in Khyber Pakhtunkhwa and Kashmir record use of leaves, resin and preparations for neuralgia, rheumatism, epilepsy, asthma, inflammation and neuropsychiatric complaints (Mir *et al.*, 2021; Jan *et al.*, 2022). These traditional indications find partial modern validation in the pharmacology of Δ^9 -tetrahydrocannabinol (THC) and cannabidiol (CBD), which act on CB1/CB2 receptors and additional non-canonical targets (Cristino *et al.*, 2020; Devinsky *et al.*, 2017; Russo, 2019). At the same time, global demand for pharmaceutical cannabinoids, hemp fibre, seed protein and bio-composites continues to rise (United Nations Office on Drugs and Crime, 2023; Chandra *et al.*, 2021).

land and therefore sits at a strategic intersection: it retains living ethnobotanical knowledge and landrace diversity in its northern districts, faces clear opportunities for industrial hemp and phytoremediation on contaminated or marginal land and must navigate legal and quality-assurance constraints that distinguish low-THC industrial cultivars from drug-type chemotypes. Yet the national research and policy landscape remains fragmented. Ethnobotanical records, phytochemical studies, tissue-culture protocols and environmental assessments are rarely integrated into a single analytical continuum that ends in measurable bioeconomy outcomes.

Cannabis Knowledge-to-Bioeconomy Nexus (CKBN) is a sequential framework that links: (1) traditional and ethnobotanical knowledge; (2) genetic and chemotypic diversity; (3) phytochemical fingerprinting; (4) compound–target–pathway networks; (5) biotechnological optimisation (micropropagation, marker-assisted selection, metabolic engineering); (6) precision cultivation; (7) pharmaceutical, nutraceutical and industrial products; (8) life-cycle and sustainability assessment; and (9–10) waste

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valorization and circular bioeconomy metrics. Each stage is associated with measurable indicators so that progress can be tracked rather than only described.

Using QGIS/ArcGIS principles we conceptualise a Pakistan Cannabis Ethnobotanical–Environmental Atlas that overlays ethnobotanical records, landrace and chemotype reports, research intensity, climate–soil context and contamination potential across Khyber Pakhtunkhwa, Gilgit-Baltistan, Punjab foothills and Balochistan. The atlas is offered as a planning layer for future field sampling, conservation of landraces and site selection for industrial hemp or phytoremediation trials.

The central question is therefore practical as well as scientific: can the ethnobotanical knowledge and genetic resources of northern Pakistan be systematically converted—through chemotypic characterisation, biotechnology and spatial planning—into sustainable pharmaceutical, fibre and environmental value chains? The sections that follow answer this question with evidence drawn from peer-reviewed literature and with explicit attention to software-supported analysis (bibliometrics, cheminformatics, network logic and GIS).

Methods and Software Stack

Literature was retrieved from Scopus, Web of Science, PubMed and Google Scholar. Bibliometric trends and keyword patterns were synthesised from published Bibliometrix and VOSviewer analyses. Chemical structures and class data were cross-checked with PubChem and related cheminformatics resources. Pathway and interaction logic followed Cytoscape/KEGG conventions. Graphs and conceptual figures were generated in Python (matplotlib). Spatial reasoning for Pakistan follows QGIS/ArcGIS layer logic (ethnobotanical points, research nodes, climate–soil context, contamination potential) and is presented as a conceptual atlas pending full open geospatial datasets (Figure 1).

Software stack applied in this review — QGIS/ArcGIS emphasised for Pakistan spatial analysis



Figure 1. Software and database stack applied in this review. QGIS/ArcGIS is emphasised for the Pakistan spatial atlas.

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The CKBN Framework

CKBN converts ethnobotanical knowledge into chemotypic, molecular, biotechnological and circular-economy value through a sequence of measurable stages (Figure 2). Indicators at each stage include publication density, chemotype coverage, micropropagation survival rates, product diversification indices and life-cycle metrics.

Figure 10. Signature framework: Knowledge-to-Bioeconomy Nexus with multi-domain data integration



Figure 2. Cannabis Knowledge-to-Bioeconomy Nexus (CKBN)—signature framework

Pakistan Spatial Focus (QGIS/ArcGIS)

Northern Pakistan—especially Swat, Dir, Chitral and Gilgit-Baltistan—hosts both living ethnobotanical practice and landrace diversity. Research and institutional nodes concentrate around universities and research centres in Khyber Pakhtunkhwa and the federal capital. Punjab foothills and parts of Balochistan offer additional environmental and cultivation contexts. A QGIS/ArcGIS-based atlas can overlay: (i) ethnobotanical and ethnoveterinary records; (ii) reported landrace or chemotype locations; (iii) publication and research intensity; (iv) climate and soil layers; and (v) contamination or marginal-land suitability for industrial hemp and phytoremediation.

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Figure 3 presents a conceptual version of this atlas; full operationalisation requires open geospatial datasets and field validation.

Pakistan Cannabis Ethnobotanical-Environmental Atlas (QGIS conceptual layers)

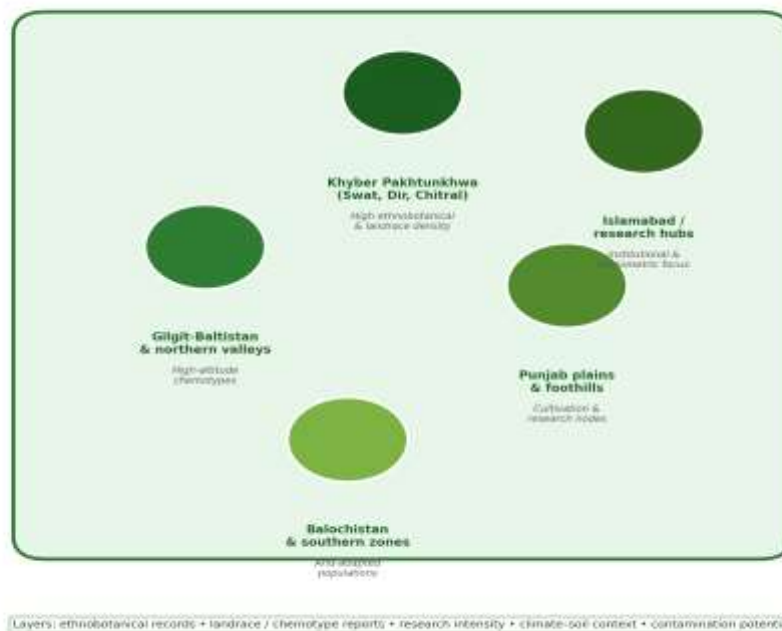


Figure 3. Pakistan Cannabis Ethnobotanical–Environmental Atlas (QGIS conceptual layers: KP/Swat, Gilgit-Baltistan, Punjab foothills, Balochistan, research hubs).

Ethnobotanical Evidence (Pakistan and Himalaya)

Surveys in Khyber Pakhtunkhwa, Kashmir and the broader Himalaya document use of leaf, resin and preparations for neuralgia, rheumatism, epilepsy, asthma, inflammation and anxiety-related conditions (Mir *et al.*, 2021; Jan *et al.*, 2021; Jan *et al.*, 2022; Bussmann *et al.*, 2021). These claims align with modern pharmacology of THC and CBD (Cristino *et al.*, 2020; Devinsky *et al.*, 2017; Russo, 2019) (Table 1).

Table 1. Selected ethnobotanical uses relevant to Pakistan and the Himalaya

Category	Indication	Plant part	Region / source
Analgesic	Neuralgia, rheumatism	Leaf, resin	KP, Kashmir, Tibet (Jan <i>et al.</i> , 2021)
Anticonvulsant	Epilepsy	Leaf, resin	India, Middle East; clinical (Devinsky <i>et al.</i> , 2017)
Respiratory	Asthma, bronchitis	Smoke, infusion	Himalayan surveys (Mir <i>et al.</i> , 2021)
Neuropsychiatric	Anxiety, hypnotic	Resin, bhang	India, Tibet (Bussmann <i>et al.</i> , 2021)

Biochemical Structures of Major Cannabinoids

More than 140 phytocannabinoids are known; Δ^9 -THC, CBD, CBG, CBC, CBN and THCV dominate research and applications (ElSohly *et al.*, 2021; Radwan *et al.*, 2021). Structures below are schematic; full stereochemistry is available in PubChem (Figure 4-5).

Major Phytocannabinoids of *Cannabis sativa* L. — Chemical Structures (schematic)

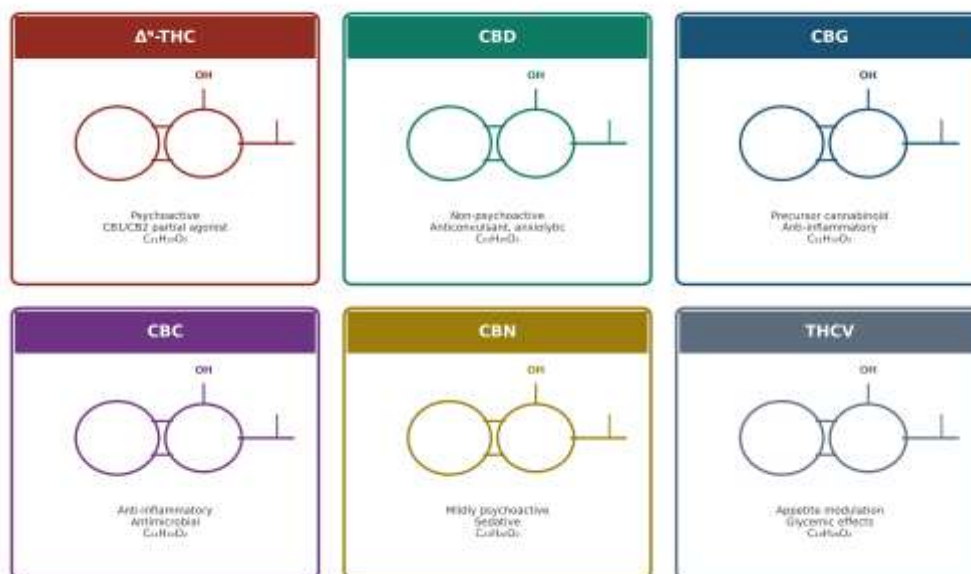


Figure 4. Schematic structures of six major phytocannabinoids (Δ^9 -THC, CBD, CBG, CBC, CBN, THCV).

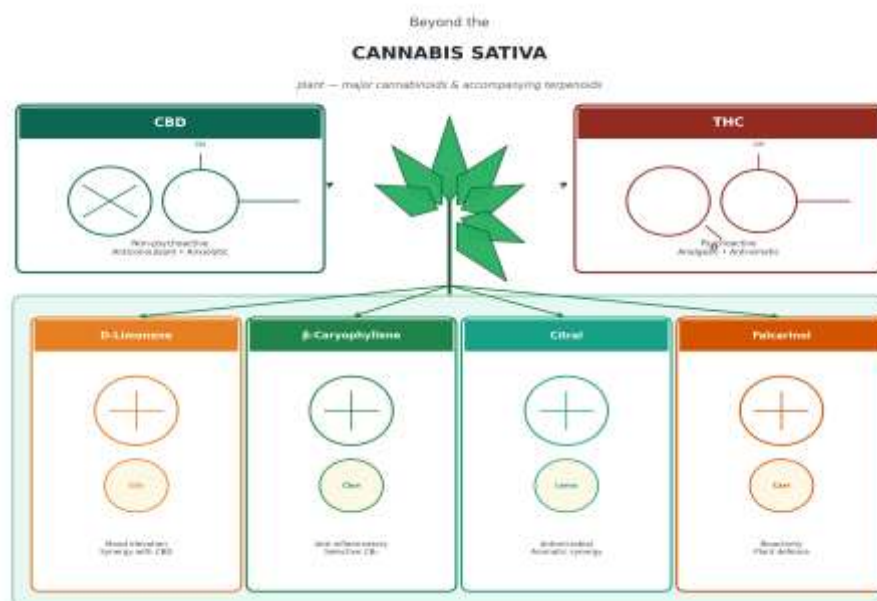


Figure 5. CBD, THC and key terpenoids (D-limonene, β -caryophyllene, citral, fenchone) contributing to the entourage effect

Biotechnology

Micropropagation on MS or DKW media with cytokinins yields 5–8 shoots per explant and >85 % ex-vitro survival (Stephen *et al.*, 2023; Page *et al.*, 2021; Monthony *et al.*, 2021). Temporary-immersion systems and marker-assisted selection improve scalability and chemotype control (Kodym & Leeb, 2019; Grassa *et al.*, 2021). For Pakistan, tissue-culture platforms can supply uniform, pathogen-free planting material of both high-CBD and low-THC industrial types while conserving northern landraces (Figure 6).

Figure 7. Biotechnology Pipeline for Elite Cannabis sativa Propagation and Metabolite Optimization



Figure 6. Biotechnology pipeline for elite propagation and metabolite optimisation.

Phytoremediation and Circular Bioeconomy

Industrial hemp accumulates Cd, Pb and Ni mainly in roots and can be grown on contaminated or marginal land (Linger *et al.*, 2002; Ansari & De Prato, 2026; Golia *et al.*, 2023). A hectare sequesters ~2.5 t CO₂ (Finnan & Styles, 2013). Residues after extraction are candidates for biochar, composites or energy. In Pakistan this dual role—fibre/seed production plus soil remediation—is especially relevant for industrial and peri-urban contaminated sites (Figure 7).

Figure 8. Sustainable Circular Bioeconomy Model for Cannabis sativa L.

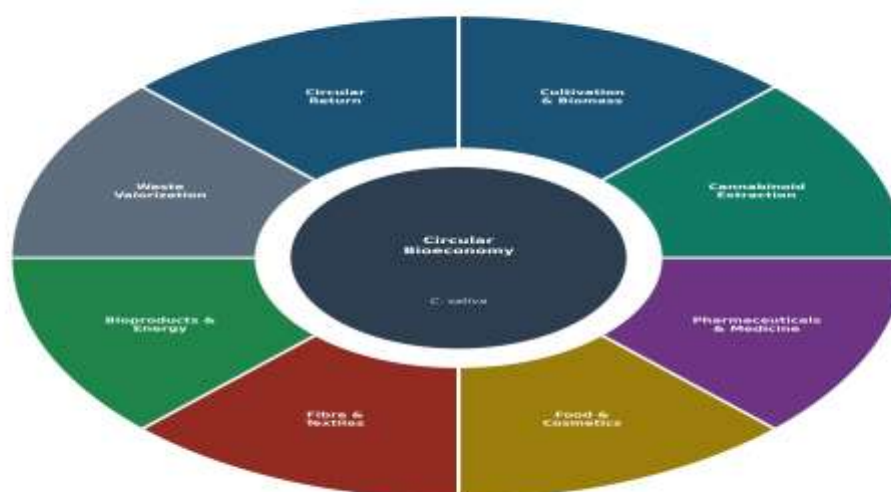


Figure 7. Circular Cannabis bioeconomy model.

Research Gaps and Priorities for Pakistan

Evidence is strongest for ethnobotany and core phytochemistry. Gaps and innovation potential are highest for: (i) field multi-omics of the *Cannabis* mycobiome in northern Pakistan; (ii) metabolic engineering and CRISPR-based chemotype control under local regulation; (iii) temporary-immersion scale-up of micropropagation; (iv) residue valorization pilots; and (v) comparative life-cycle assessment of pharmaceutical versus industrial production under Pakistani climatic and legal conditions (Table 2).

Table 2. Priority research gaps (Pakistan-relevant)

Domain	Evidence	Major gap	Priority action for Pakistan
Ethnobotany (KP/GB)	Moderate–high	Standardised documentation	District-level surveys + GIS layers
Landrace chemotype	Limited	Georeferenced chemotype data	Sampling + QGIS atlas
Micropropagation	Protocols exist	Local scale-up, cost	Temporary-immersion pilots
Phytoremediation	Global evidence	Pakistan field trials	Contaminated-site pilots
Circular / LCA	Limited	Local LCA data	Residue + climate-specific LCA

Conclusion

CKBN links the ethnobotanical knowledge and landrace resources of northern Pakistan to chemotypic characterisation, biotechnology and circular bioeconomy outcomes. With QGIS/ArcGIS spatial layers, bibliometric and cheminformatic tools, and clear research priorities, the framework offers a practical roadmap for converting traditional knowledge into sustainable pharmaceutical, fibre and environmental value chains under Pakistani conditions.

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