Peat and peatlands research in India: A review on present status and future prospects

Alok Kumar[1], Kimon Christanis[2], Prakash K. Singh[1]

[1] MP Singh Lab of Coal and Organic Petrology, Department of Geology, Banaras Hindu University, Varanasi, India
[2] Department of Geology, University of Patras, Greece

SUMMARY

Energy security and environmental sustainability are now crucial strategies for emerging countries like India. Peat is a versatile geo-material that can serve as a fossil energy source and industrial raw material used in horticulture/agriculture, but also as an archive of geological and palaeoenvironmental records. At the same time, peatlands globally play a critical role in carbon storage, water regulation and biodiversity. Peatlands in Southeast Asian countries (primarily Indonesia and Malaysia) are extensively studied, but in India peatland is a relatively obscure ecosystem and one of the least studied geological environments. This review aims to summarise the peat and peatland research that has been done so far in India. We find that peatlands have been studied in parts of Himachal Pradesh, Uttarakhand, Arunachal Pradesh, Assam, Manipur, Tripura, Kerala, Tamil Nadu and West Bengal. However, India has no centralised comprehensive database on peatlands. In fact, the study and inventory of peatlands in India remains significantly under-developed in terms of global standards, resulting in limited availability of information about the locations, extent and characteristics of these ecosystems. Active development of peat and peatlands research in India could benefit carbon storage and climate regulation bodies, water storage and supply organisations, biodiversity conservation agencies, flood control and prevention agencies, fish farming and agriculture, as well as the energy sector.

KEY WORDS: carbon, climate, energy, GIS, inventory, mire, palaeoenvironment

INTRODUCTION

Peat is a spongy material formed from partially decomposed plant-tissue remains accumulating sedentarily in mires (Grosse-Brauckmann 1990). The plant remnants have not decomposed completely owing to the waterlogged conditions that dominate in mires, which limit the activity of aerobic microbial decomposers. This results in some of the organic material initially contained in the helophytic plants accumulating as a peat deposit (Visser 1969, Fisk *et al.* 2003). Natural (living) mires are highly dynamic ecosystems that provide important habitats for a variety of wildlife and archive information about past environmental conditions (Naafs *et al.* 2019). These wetland systems are also humankind's potential ally in the fight against climate change.

An area of land with a surface peat layer of defined minimum thickness (differing between countries) is called a peatland. Peat accumulation is a slow process and it can take 1000 years to form a peat layer 1 m thick (e.g., Gorham *et al.* 2003, Naafs *et al.* 2017), but the process has typically continued for several millennia. Because peat consists of carbon-rich organic matter, a large amount of carbon is stored in peatlands (Leng *et al.* 2019) and their carbon density can be greater than in other ecosystems. For example, Canada's northern peatlands store five times more carbon per square metre than the Amazon rainforest (Sothe *et al.* 2022). Indeed, although peatlands cover only around 3 % of the global land surface (Maltby & Proctor 1996, Joosten & Clarke 2002, Page *et al.* 2007, 2011), they are estimated to store 15–30 % of all soil carbon globally (Leifeld & Menichetti 2018). Thus, through ancient, modern and future geological processes, peatlands serve as one of Earth's most significant repositories of organic carbon, playing a vital role in the global carbon cycle (Omar *et al.* 2022). They have recently attracted attention because they are estimated to store significantly more carbon than any other terrestrial ecosystem (Beaulne *et al.* 2021), and this makes them crucial for climate regulation.

Drought episodes retard or even arrest peat accumulation in mires, changing the nature of the ecosystem. The rate of aerobic decomposition increases due to re-exposure of the recently formed peat to atmospheric oxygen. This facilitates the breakdown of stored carbon, resulting in enhanced release of CO_2 into the atmosphere and slowing of the (net) peat accumulation rate. Even if the peat-forming mire vegetation has disappeared (e.g., through land use change) the peat layer can remain in place, but decomposition will resume if it dries out. Because new peat is no longer being formed, the peat layer will then start to disappear (oxidise), releasing CO_2 that was sequestered during millennia back into the atmosphere over a much shorter period. Allowing peatlands to recover from disturbance is considered a viable option for naturally lowering greenhouse gas emissions (Waldron *et al.* 2019). However, due to anthropogenic degradation, they are at risk of instead becoming a massive new source of greenhouse gas emissions (Dunn & Freeman 2011).

Beyond carbon sequestration, peatlands act as natural water filters, improving the quality of fresh water feeding streams, rivers and lakes (Ritson *et al.* 2016). They are also extremely useful archives of information relevant to the reconstruction of past environmental conditions, since they record specific climatic and geological events (e.g., Christanis 1983, Hoş-Çebi & Korkmaz 2015, Kern *et al.* 2022). Peatlands in both temperate and tropical regions harbour remarkable ecological records which are often used for palaeoclimate reconstruction (Kumaran *et al.* 2016). In fact, peat-based proxies can be accessed through not only palaeobotany and palynology but also via sedimentology, organic and inorganic geochemistry, organic petrology, isotope signatures, etc. (Nichols *et al.* 2006, Pancost *et al.* 2011, Chambers *et al.* 2012, Väliranta *et al.* 2012, Burrows *et al.* 2014, Cristea *et al.* 2014, Huguet *et al.* 2014, Zocatelli *et al.* 2014, Hansson *et al.* 2015, Roland *et al.* 2015, Zheng *et al.* 2015, Jordan *et al.* 2017). Some examples are outlined below:

- Sedimentary studies, including grain size and clay minerals analyses, offer valuable insights into past environmental and climatic conditions (Sun *et al.* 2006, Kong *et al.* 2011).
- The concentrations of major, minor and trace elements serve as an effective proxy for tracing sediment sources and deciphering palaeoenvironmental conditions during peat accumulation (Lei *et al.* 2017).
- The *n*-alkane distribution and geochemical indices including Carbon Preference Index (CPI), Terrigenous Aquatic Ratio (TAR), aquatic plant *n*-alkane proxy (Paq) and vascular plant *n*-alkane proxy (Pwax), obtained from the analysis of organic extracts by the PY-GC and GC-MS techniques, shed light on the origins of organic matter in peat along with the associated depositional settings and palaeoclimatic conditions (Ficken *et al.* 1998, 2000; Pancost *et al.* 2002, 2007; Peters *et al.* 2005, Zhou *et al.* 2005, Bingham *et al.* 2010, Inglis *et al.* 2015, Baker *et al.* 2016, Naafs *et al.* 2019, He *et al.* 2019).
- Organic petrology is another effective technique for precisely reconstructing palaeoenvironmental and palaeovegetational conditions (Dehmer 1993, 1995; De Vleeschouwer *et al.* 2008, Hoş-Çebi & Korkmaz 2015, Singh & Kumar 2017, Kumar *et al.* 2020, 2024).
- Diatom analysis is applied to reconstruct hydroclimatic conditions and monitor peat degradation patterns (Chen *et al.* 2020, Li *et al.* 2020).
- Palynomorphs (e.g., spores, pollen and phytoplankton), phytoclasts and amorphous organic matter are important analytical proxies for reconstructing past vegetation types (Khandelwal *et al.* 2008).
- Stable carbon isotope ratios ($\delta^{13}C$), radiocarbon dating and magnetic susceptibility contribute to reconstructing palaeovegetation, palaeoclimate and palaeotemperature development along peat profiles to elucidate the atmospheric carbon cycle of the past (Oldfield *et al.* 1978, 1981; Williams 1992, Pancost *et al.* 2000, Rühland *et al.* 2000, Blaauw & Christen 2005, Kokfelt *et al.* 2009, Gaiser & Rühland 2010, Charman *et al.* 2012, Fukumoto *et al.* 2012, Cristea *et al.* 2014, Hargan *et al.* 2015a, 2015b; Chen *et al.* 2016, Hentschel *et al.* 2016, Chen *et al.* 2020, Li *et al.* 2020).

In some countries peatlands are used for drainage-based agriculture, or the peat is mined for use as fuel and/or for manufacturing soil conditioners and other carbon-based products, as well as for water treatment (Joosten & Clarke 2002). Nowadays, however, across the world from Southeast Asia through Europe to North America and beyond, these consumptive uses are being superseded by rewetting or full restoration of degraded peatlands to regain some of the increasingly valuable ecosystem services they provide when less profoundly disturbed (e.g., UNEP 2022).

In India, peatlands have been reported from several regions (Thomas *et al.* 1974, Sukumar *et al.* 1993, Rajagopalan *et al.* 1997, Jain *et al.* 2000, Narayana *et al.* 2002, Bhattacharya *et al.* 2021, Srivastava *et al.* 2017, Das *et al*. 2022, Paul *et al.* 2022). However, information about the types and sizes of peatlands, their peat-forming flora and ecology, their carbon dynamics (storage versus emissions), energy potential and functions for environment and climate is difficult to find. Also, there seem still to be many gaps in knowledge about the size and status of the country's peat resource. In addition to the peatlands that can be found in today's landscape, peat may also have been covered by younger inorganics and so be hidden beneath other Quaternary sediments (Narayana *et al.* 2002, Kumaran *et al.* 2016).

Very limited research has been carried out to assess the potential climatic and environmental effects of the recently proposed exploitation of peat resources in India for energy (Sawant *et al.* 2021, Paul *et al.* 2022, Agarwal *et al.* 2023, Sagwal *et al.* 2023). Therefore, it is now crucial to study India's peatlands owing to their significance for climate and environment combined with the new prospect of their utilisation as a source of energy peat.

This study reviews the existing research literature on Indian mires, peatlands and peat deposits, paying special attention to information about site locations (which are mapped) and summarising the topics of research along with findings. It also highlights the potential importance of peatlands for India, focusing on carbon dynamics, biodiversity support, other environmental services and energy production.

REVIEW AND MAPPING PROCEDURE

The review involved a systematic literature search and geospatial mapping. Peer-reviewed articles, government reports and other literature were collected from databases such as Web of Science, Scopus and Google Scholar using search terms like 'peat', 'peatlands', 'India', 'carbon storage', 'Holocene' and region-specific terms. Inclusion criteria were: (i) presence of georeferenced data or specific location descriptions; (ii) reporting of peat properties or palaeoclimatic proxies; and (iii) publication in English. Studies lacking location data or focusing solely on non-peat organic soils were excluded. Coordinates were either extracted from the literature or estimated from maps, and compiled into a comprehensive peat location map prepared using ArcMap 10.2.2 (Figure 1, Table 1).

DISTRIBUTION OF STUDIES REVIEWED

Peatlands in India are reported to extend from coastal areas around the Bay of Bengal and Arabian Sea to the foothills of the Himalayas (Rieley & Page 2016). According to Bhattacharyya *et al*. (2025; source https://icar.org.in/hi), the total area of peatlands nationally is approximately 88,756 km^2, accounting for 2.17 % of the land area of the country. Most peatlands have not yet been properly mapped or inventoried, and studied peatlands are scarce.

In the north (Table 1, Figure 1), peat studies have been reported from the Dokriani periglacial area in Garhwal (Higher Himalaya Region); the Dhakuri peatland in Pinder Valley, Kumaon; near Kedarnath Temple; in Baspa Valley, Himachal Pradesh; and at Leh/Stagmo in Ladakh (Phadtare 2000, Phadtare & Pant 2006, Srivastava *et al.* 2017, Khan *et al.* 2022, Agarwal *et al.* 2023). In the south-west, studied peatlands are located in Nilgiri Hills, particularly Sandynallah Basin in Tamil Nadu State (Sukumar *et al.* 1993); and Vembanad Lake, Alappuzha Basin, Periyar Basin in Kerala (Narayana *et al.* 2002). In eastern India, peat has been studied in West Bengal at Barrackpore in the 24-Parganas district and at the Garia metro railway excavation site near Sundarbans (Sen & Banerjee 1984, Das 2009, Das 2014). In the north-eastern part of the country, peat is reported from Assam at NH39 near Saint Capitanio School (Cachar District), Kalinagar Tea Estate in Hailakandi District; and Borjalenga-Nayabeel in Silchar. In other north-eastern states, peat was studied at Chairipara in Tripura at the Indo-Bangladesh Border; at the National Institute of Technology in Manipur (Paul *et al.* 2018, 2022); and in Anunachal Pradesh (Kar *et al.* (1997), De *et al.* (2001), Das *et al.* (2022).

REGIONAL SYNOPSES

Northern Region

Various researchers have dated peat in the Northern Region at between 10936 and 254 cal yrs BP, by applying ^{14}C AMS dating (Phadtare & Pant 2006, Rühland *et al.* 2006, Rawat *et al.* 2015, Srivastava *et al.* 2017, Khan *et al.* 2022). Their studies, also including analyses of pollen, diatoms, magnetic susceptibility, δ^{15}N and δ^{13}C, indicated alternating episodes of wet and warm with cold and dry climatic conditions during peat accumulation (Phadtare 2000, Phadtare & Pant 2006, Srivastava *et al.* 2017, Khan *et al.* 2022, Sagwal *et al.* 2023). Bhattacharya *et al.* (2021) used *n*-alkanes to determine that peat had accumulated in suboxic depositional environments.

Palaeoclimatic studies of peatlands in the Central Higher Himalaya section of the Himalayas reveal Holocene-age variations in intensity of the Indian Summer Monsoon (ISM) based on analysis of peat profiles (Phadtare 2000, Phadtare & Pant 2006, Bhattacharya *et al.* 2021, Khan *et al.* 2022, Agarwal *et al.* 2023) (Table 2). Phadtare (2000) studied pollen from an alpine peat profile near Dokriani Glacier in Garhwal, Higher Himalaya. The investigation focused on magnetic susceptibility and age-constrained pollen records. The magnetic susceptibility data served as an indicator of detrital

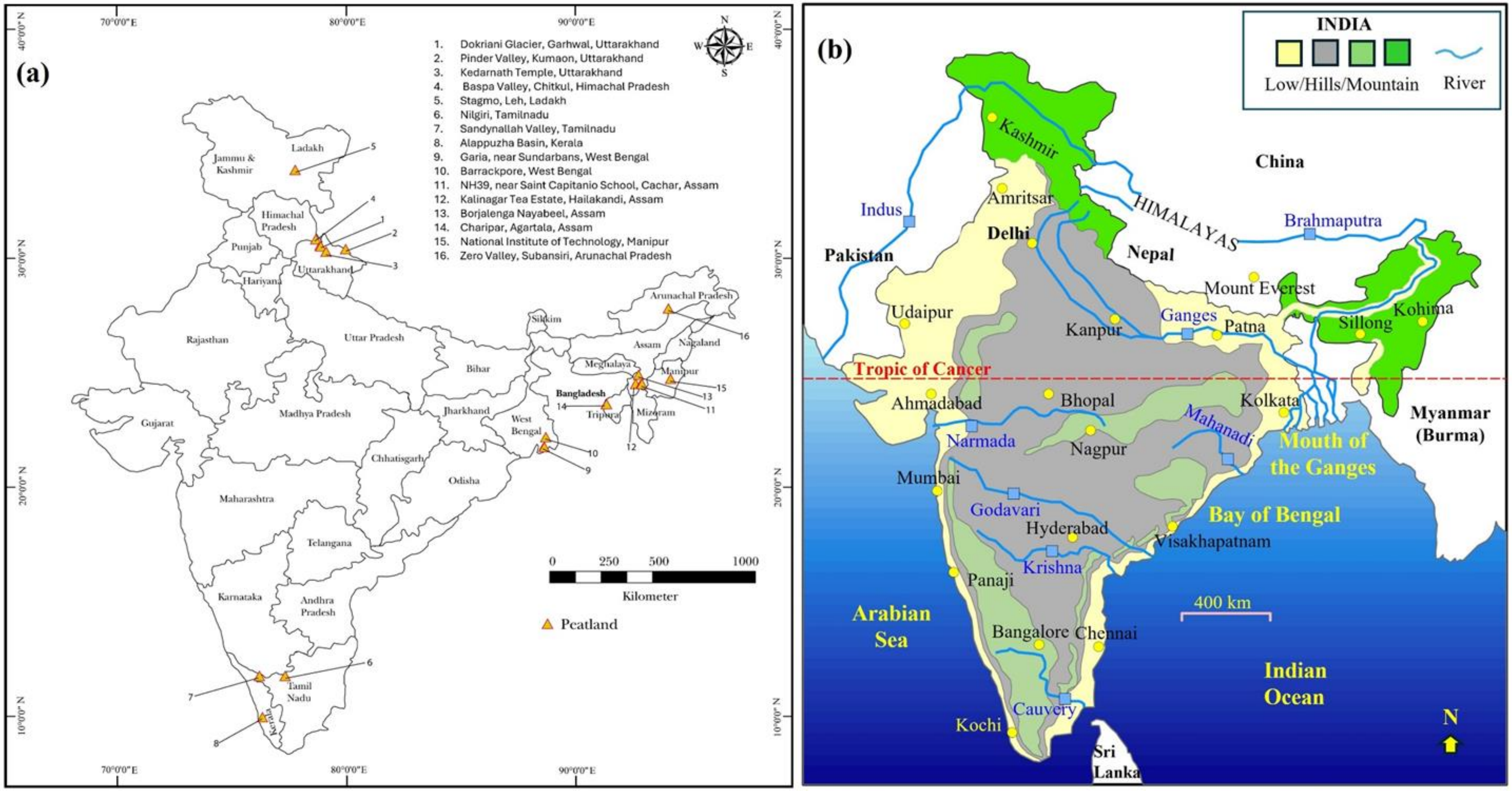

Figure 1. (a) Schematic map of India showing known locations with peat deposits, and (b) map of India indicating its geographical position relative to terrain features including the Himalayas, the Indian Ocean and river systems (redrawn from WorldAtlas.com).

mineral influx related to catchment erosion. Higher magnetic susceptibility values reflected increased runoff during more-intense monsoon periods, while lower values suggested decreased mineral input and milder monsoon conditions. The continuous 7800-year record revealed monsoon and climate trends, initially showing a prevalence of evergreen oak, alder and grasses, which reflect a cold, wet climate with moderate monsoon precipitation. Between 7800 and 5000 years BP, the dominance of conifers suggests an overall improvement in climate driven by more pronounced monsoon influence. Specifically, from 6000 to 4500 years BP, the monsoon reached its maximum strength, leading to a warm and humid climate. However, the abundance of conifers sharply declined from 4000 to 3500 years BP. Around 3500 years BP, the minimum rainfall and the coolest climate reflected the weakest monsoon phase of the Holocene record. Phadtare & Pant (2006) reconstructed the climate and vegetation history of the past 3500 years from a century-scale pollen record obtained from peat (1.2 m thick) in the Pinder Valley Dhakuri in Kumaon, Higher Himalaya. The valley's climate was cold from 3500 to 1600 years BP, marked by two distinct dry episodes (3300–2300 and 2100–1600 years BP).

Most records of the ISM that span the Holocene are obtained from cave deposits in peninsular India, Arabian Sea sediments, and peat sequences from central and north-western India (Anderson *et al.* 2002, Gupta *et al.* 2003, Sinha *et al.* 2007, Rawat *et al.* 2015). Srivastava *et al.* (2017) identified the earliest Holocene climatic variability of the ISM, based on ^{14}C-dated peat deposits (5.2 m thick,

Table 1. The studied peatlands in India per region.

Region	State	District/Locality	Coordinates	Map number
Northern	Uttarakhand	Garhwal/Higher Himalaya, Dokriani Glacier	30°50′–30°52′N, 78°47′–78°51′E	53I16
		Kumaon/Dhakuri, Pinder Valley	30°48′N, 79° 55′E	53N10
		Rudraprayag/near Kedarnath Temple	30°43'48"N, 79°3'36" E 30°44'6.7"N, 79°04'1"E	53N2 53N2
	Himachal Pradesh	Kinnaur/Chitkul, Baspa Valley	31°21'00"N, 78°28'12"E	53I7
	Ladakh	Leh/Stagmo	34°06'12"N, 77°41'26"E	52F12
South-Western	Tamil Nadu	Nilgiri/Sandynallah Basin	11–11° 30'N, 76–77° 20'E	58E7
		Sandynallah Valley	11°26'32"N, 76°38'06"E 11°26'37"N, 76°38'08"E	58A11 58A11
	Kerala	Laccadive/Alappuzha Basin	9°13.624'N, 76°32.533'E	58C12
Eastern	West Bengal	South 24-Parganas/Garia, near Sundarbans	22°28′–21°45′N 88°23′–88°15′E	79C6
		North 24-Parganas/Barrackpore	22°50'N, 88°18'E	79B5
North-Eastern	Assam	Cachar/ NH39 near Saint Capitanio School	24°49'38"N, 92°47'52"E	83D13
		Hailakandi/Kalinagar Tea Estate	24°41'49"N, 92°33'51"E	83D10
		Silchar/Borjalenga-Nayabeel	24°67′56″N, 92°43′97″E	83C16
	Tripura	Agartala/Charipara, Indo-Bangladesh Border	23°49'45"N, 91°16'40"E	79M5
	Manipur	Imphal/National Institute of Technology	24°48'50"N, 93°57'11"E	83H13
	Arunachal Pradesh	Subansiri/Zero Valley	26°36'N, 93°15'E	83F6
		Subansiri/Hapoli area	27°32'30"N, 93°49'24"E	83E14
		Subansiri/Bre area	27°36'N, 93°15'E	83E6
		Subansiri/Soro area	27°31'30"N, 93°15'30"E	83E3

spanning the last 8000 years) from the Higher Himalaya Region near the Kedarnath Temple. These researchers applied a high-resolution multi-proxy approach to reconstruct ISM, revealing similarities with contemporary climate records extending from Greenland to the equatorial South Pacific (Peru Margin). Khan *et al.* (2022) studied monsoonal (ISM) variability from the late Pleistocene to the Holocene using various proxies from a 100-cm-thick peat layer found in Chitkul, Baspa Valley, Himachal Pradesh, Northwest Himalaya. The total organic carbon content, $\delta^{13}C$, ^{14}C and the magnetic data indicated that variability in solar radiation in the Northern Hemisphere played a key role in driving climate change in terms of ISM variation during the middle to late Holocene.

Bhattacharya *et al.* (2021) examined the vegetation history of a 5-m-thick peat sequence from Kedarnath Region (Garhwal, Himalaya) using molecular fossil proxies. The biomarker investigation revealed that the organic material forming the peat consisted of gymnosperms, *Sphagnum* sp. and lipid components. The *n*-alkane ratios indicated a shift in monsoon intensity alongside a corresponding change in the vegetation cover. Agarwal *et al.* (2023) dated a 5.4 m peat sequence near the Kedarnath Temple in Central Himalaya spanning the period from middle to late Holocene and conducted a study on diatoms within the peat using high-resolution data to reconstruct the palaeoclimate. Their observations suggested that drier environmental conditions prevailed at Kedarnath during the middle Holocene, while two longer wet phases were noted during the late Holocene. Diatom concentrations declined steeply during the period 679–300 years BP, pointing to dry conditions. The observed decrease in diatom

Table 2. Peatlands in the Northern Region of India. NA: not available; TOC: Total Organic Carbon content, TN: Total Nitrogen content, AMS: Accelerator Mass Spectroscopy.

Peatland locality	Age (in cal yrs BP)	Peat type/ vegetation	Climatic & depositional conditions	Proxy used	Reference
Garhwal/Central Higher Himalaya, Dokriani Glacier	7800-800 (mid-late Holocene)	NA	alternation of wet/warm and cold/dry episodes	palynology	Phadtare (2000)
Kumaon/Dhakuri, Pinder Valley	3500-57 7515-370 (mid-late Holocene)	*Sphagnum* sp.,gymno-sperms	alternation of wet/warm and cold/dry episodes; suboxic depositional environment	palynology, diatom, magnetic susceptibility, ^{14}C AMS dating, *n*-alkanes	Phadtare & Pant (2006), Rühland *et al.* (2006), Bhattacharya *et al.* (2021)
Rudraprayag/ near Kedarnath Temple	8077-370 (mid-late Holocene)	NA	alternations of wet/warm and cold/dry episodes	^{14}C AMS dating, diatoms	Agarwal *et al.* (2023)
Kedarnath Region	6500-300 (mid-late Holocene to Recent)	fibrous peat	alternations of wet/warm and cold/dry episodes	^{14}C AMS dating, magnetic susceptibility, TN, TOC, $\delta^{15}N$, $\delta^{13}C$, palynology	Srivastava *et al.* (2017)
Kinnaur/Chitkul, Baspa Valley	10936-376	NA	wet and warm climate	^{14}C AMS dating, $\delta^{13}C$, TOC	Khan *et al.* (2022)
Leh/Stagmo	2810 and 1370 (late Holocene)	NA	warm/humid climate, cold-desertic at present	charcoal count, AMS ^{14}C dating, $\delta^{13}C$, $\delta^{15}N$, TOC, TN	Sagwal *et al.* (2023)
Chandra Valley, Lahaul	4420-254 (mid-late Holocene to Recent)	NA	warm climate	AMS ^{14}C dating, magnetic susceptibility	Rawat *et al.* (2015)

counts suggested that lower diatom abundance was associated with reduced organic content and enhanced decomposition. This change affected the quality of the peat, which was assessed here in terms of organic content, level of decomposition (humification) and potential for use in agriculture or as fuel.

South-Western Region

Tropical peatlands are well documented across the world, especially in Southeast Asia (e.g., Leng *et al.* 2019), but those on the Indian subcontinent have attracted little attention so far. Peatlands in the South-Western Region of India were formed primarily by evergreen tropical forests that formed freshwater mires during the Holocene (Kumaran *et al.* 2014). Peatlands near the south-west coast have been dated back to between 40,000 and 311 cal yrs BP (Sukumar *et al.* 1993, Rajagopalan *et al.* 1997, Narayana *et al.* 2002, Bala *et al.* 2016). Arid-humid climatic conditions and freshwater environments were reported from some parts of the south-west coast by Sukumar *et al.* (1993), Narayana *et al.* (2002) and Kumaran *et al.* (2016). Peat deposits in this vicinity have been classified as tropical minerotrophic, formed primarily from mangrove remains during the late Pleistocene to mid Holocene (Mascarenhas 1997, Kumaran *et al.* 2016). A 2.4 m tropical peat sequence from Nilgiri Region in southern India was examined by Sukumar *et al.* (1993) and Rajagopalan *et al.* (1997), focusing on vegetation and climate changes and using stable carbon isotope data. Sukumar *et al.* (1993) introduced a 20,000-year-long $\delta^{13}C$ record derived from peat samples in the Nilgiri Hills (Sandynallah Basin) of southern India (Table 3). Their findings indicated a significant climate change during the Last Glacial Maximum (18,000 years ago) and the subsequent deglaciation. They also noted a dry phase between 6000 and 3500 years ago and a short wet phase approximately 600 years ago.

The primary technique applied in palaeoclimate studies to determine age-depth relationships using peat samples has been radiocarbon dating (Blaauw & Christen 2005, Bala *et al.* 2016). Mascarenhas *et al.* (1993) and Mascarenhas (1997) studied a 20 cm peat sequence from the western shelf and coast of India to shed light on the palaeodepositional setting. Their findings indicated sediment reworking and suggested that organic debris was being moved to offshore areas. As a result, the peat layer could not be classified as a transgressive deposit and was not a reliable indicator for Holocene Sea level rise. They also concluded that peat is the main source of gases in the Holocene sediments on the continental shelf of India. Narayana *et al.* (2002) investigated three peat layers (3 m, 5.5 m and 5 m thick) from 30 m depth below ground surface on the south-west coast of Kerala. Radiocarbon dating and palynological analysis suggested that humid climatic conditions and mangrove vegetation dominated around 40,000 years BP. Kumaran *et al.* (2016) examined a tropical peat deposit 2–3 m thick at 7 m depth in the Greater Pamba Basin of south-western India. Applying palynological analysis, radiocarbon dating and isotope analysis ($\delta^{13}C$, $\delta^{15}N$) revealed that this was Middle Holocene (7000–6500 years BP) peat that accumulated in a freshwater mire.

Table 3. Peatlands in the South-Western Region of India. NA: not available; XRD: X-Ray Diffraction; TS: Total Sulfur content; AMS: Accelerator Mass Spectroscopy.

Peatland locality	Age (in cal yrs BP)	Peat type/ vegetation	Climatic & depositional conditions	Proxy used	Reference
Nilgiri Hills/ Sandynallah Basin	20000–311 (early Holocene to Recent)	minerotrophic tropical peat	arid climate	$\delta^{13}C$, ^{14}C AMS dating	Sukumar *et al.* (1993), Rajagopalan *et al.* (1997), Bala *et al*. (2016)
Greater Pamba Basin	7000–3200 (mid-late Holocene)	tropical peat	humid climate	C, N, $\delta^{13}C$, $\delta^{15}N$, palynology	Kumaran *et al.* (2014, 2016)
Vembanad Lake, Kerala	40000 (late Pleistocene)	NA	humid climate	^{14}C dating, palynology	Narayana *et al.* (2002)
Inner continental shelf between Goa and Mangalore	9630-8750	mangrove peat	NA	TS, XRD, major and trace elements	Mascarenhas (1997)

Eastern Region

The Lower Bengal Basin, including the Indo-Gangetic Plain, is the catchment for the Ganga, Brahmaputra and Meghna Rivers. This network of distributaries and tributaries forms the world's largest delta at the Bay of Bengal, hosting a diverse and dense mangrove ecosystem (Das 2014). Mangroves in the tidal areas of tropical coasts constitute a well-known peat-forming plant assemblage storing significant amounts of organic matter (OM). Under waterlogged anaerobic conditions, the OM accumulates and forms peat. Peatlands in the Eastern Region have been dated back to between 7000 and 2600 cal yrs BP (Das 1961, Chanda & Mukherjee 1969, Mukherjee 1972a,b, Vishnu-Mittre & Gupta 1972, Barui 2011, Das 2009, 2014). Their peat is primarily derived from mangrove vegetation (Barui 2011). They occupy freshwater environments with brackish water influence and experience warm climatic conditions (Chanda & Mukherjee 1969, Vishnu-Mittre & Gupta 1972, Sen & Banerjee 1984).

Ghosh (1964), Sen & Banerjee (1984), Banerjee & Sen (1986), Barui & Chanda (1979, 1982, 1984, 1992, 1995), Barui & Sengupta (2004), Barui (2011), Das (2009, 2014) and Reddy *et al.* (2014) studied peatlands in the Bengal Basin, focusing on palaeoenvironmental and palaeoecological features (Table 4). Sen & Banerjee (1984) investigated reptile remains found in a 1 m thick peat layer at 5.5 m depth in Barrackpore (24-Parganas District, West Bengal). The vertebrate remains indicated that a freshwater environment prevailed during peat accumulation. Various researchers had previously attempted to reconstruct the Quaternary palaeoenvironment and establish a palynostratigraphic profile of the Bengal Basin by studying the peat layer. Mallik (1969) investigated the microflora in peatlands at different locations in Kolkata, revealing that this peat was devoid of mangrove plant remains. Chanda & Mukherjee (1969) & Mukherjee (1972a,b) studied peatlands at several locations in the lower Bengal Basin and constructed pollen diagrams. Vishnu-Mittre & Gupta (1972) suggested a freshwater depositional environment based on pollen diagrams from a 1 m peat sequence located around 2 m beneath the surface in the Bengal Basin. Gupta (1978) and Gupta & Sharma (1982) reported 3–5 pollen assemblages from peatland and associated sediments in Barrackpore, Namkhana and Kolara which revealed diverse ecological phases of vegetation in the Bengal Basin during the Late Quaternary period. Radiocarbon dating showed that peat accumulation took place between 7000 and 2000 years BP.

In Quaternary palynology, stratigraphic sequences are correlated and environmental changes are reconstructed applying precise radiocarbon dating (Das 2014). To deduce past climatic phases and vegetation, fossil pollen data is compared with contemporary pollen records. Das (2009, 2014) employed a palaeoecological approach, focusing on pollen morphology and ^{14}C dating, to investigate ~0.6-m thick peat sequences from the Garia metro railway excavation site near Sundarbans in the Lower Bengal Basin. The study revealed that the lowermost (relatively uniform) peat layer (7000–6500 years BP) was formed predominantly by mangroves. In contrast, the middle peat layer (6450–6100 years BP) accumulated in a halophytic marshy wetland dominated by mangroves, ferns and some terrestrial plants. No evidence of either of these wetland

Table 4. Peatlands in the Eastern Region of India. NA: not available.

Peatland locality	Age (in cal yrs BP)	Peat type/ vegetation	Climatic & depositional conditions	Proxy used	Reference
Garia near Sundarbans, Lower Bengal Basin	7000–2600	mainly mangroves	brackish and freshwater influenced halophytic, telmatic/marshy to terrestrial	^{14}C dating, palynology	Das (1961, 2009, 2014), Chanda & Mukherjee (1969), Mukherjee (1972a,b)
Rajarhat area, N-24 Paraganas	6530–2665	mainly mangroves	NA	^{14}C dating, palynology	Barui (2011)
Barrackpore, N-24 Paraganas	NA	NA	warm climate, freshwater conditions	palynology	Sen & Banerjee (1984)
Sankrail and Jangalpore	5810–2615	NA	freshwater condition	palynology	Vishnu Mittre & Gupta (1972)

habitats was found in the upper peat layer (2600 years BP), indicating relatively dry environmental conditions during the final stage of deposition.

The intricate environmental characteristics of Eastern India such as geological structure, climate, soil composition, forest history and biotic variables have influenced the vegetation (Sanyal *et al.* 2024). Barui (2011) studied a 0.7 m peat sequence from 2–3 m depth beneath the surface in Rajarhat (North-24 Parganas) to gain insights about the floral diversity of mangroves and their relevance to palaeoenvironment in the Bengal Basin during the Holocene. Pollen analysis combined with radiocarbon dating of peat revealed a predominance of mangroves accompanied by some freshwater elements and ferns. This study also confirmed that the collected samples originated during the Holocene epoch, dating back to 6300–2665 years BP.

North-Eastern Region

Of the several researchers who have investigated north-eastern peatlands, a few have reported ages for the peat, which dates back to between 40,000 and 3800 cal yrs BP (Kar *et al.* 1997, De *et al.* 2001, Das *et al.* 2022). However, most of the peat research in this region has focused on physical and chemical properties (Paul & Hussain 2019a, 2020; Paul *et al.* 2018, 2022).

Paul *et al.* (2018, 2022), Paul & Hussain (2019a,b, 2020) and Khanday *et al.* (2021) studied microstructural characteristics as well as physical-chemical and geotechnical properties of peats in Assam (NH39, Cachar District; Kalinagar Tea Estate, Hailakandi District), Tripura (Indo-Bangladesh Border, Chairipara) and Manipur (National Institute of Technology) to understand their stability and binding properties (Table 5). They also considered

Table 5. Peatlands in the North-Eastern Region of India. NA: not available, FESEM-EDX: Field-emission scanning electron microscopy-energy dispersive X-ray spectroscopy, XRD: X-ray diffraction, FTIR: Fourier transform infrared spectroscopy

Peatland locality	Age (in cal yrs BP)	Peat type/ vegetation	Climatic & depositional conditions	Proxy used	Reference
Cachar/NH39 near Saint Capitanio School	NA	NA	NA	FESEM-EDX, XRD, FT-IR, physical-chemical properties	Paul & Hussain (2019a,b, 2020), Paul *et al.* (2018, 2022)
Hailakandi/ Kalinagar Tea Estate	NA	NA	NA	FESEM-EDX, XRD, FT-IR, physical-chemical properties, proximate analysis, calorific value	Paul & Hussain (2019a,b, 2020), Paul *et al.* (2018, 2022)
Silchar/Borjalenga-Nayabeel	NA	NA	NA	proximate analysis, calorific value	Paul *et al.* (2018, 2022)
Agartala/Charipara, Indo-Bangladesh Border	NA	NA	NA	FESEM-EDX, XRD, FT-IR, physical-chemical properties, proximate analysis, calorific value	Paul & Hussain (2019a,b, 2020), Paul *et al.* (2018, 2022)
Imphal/National Institute of Technology	NA	NA	NA	FESEM-EDX, XRD, FT-IR, physical-chemical properties, proximate analysis, calorific value	Paul & Hussain (2019a,b, 2020), Paul *et al.* (2018, 2022)
Subansiri/ Zero Valley	40000	pteridophyte, gymnosperm, angiosperm	moist sub-tropical	palyno-assemblage	Kar *et al.* (1997), De *et al.* (2001)
Subansiri, Hapoli area	10000–3800	ombrotrophic, minerotrophic	warm-humid	^{14}C dating, chemical analysis, $\delta^{13}C$, $\delta^{15}N$, geochemistry	Das *et al.* (2022)

the utilisation potential of a 2–6 m peat layer at depth 2–3 m in the North-Eastern Region. This research identified such peat deposits as a promising alternative energy source for rural areas, that could potentially replace wood fuel and sustain local power plants for years.

Paul & Hussain (2020) also chemically treated peat from the North-Eastern Region to improve its strength and binding properties, and studied its morphological properties after treatment. Khanday *et al.* (2021) published a review discussing the stabilisation of peat, as its low shear strength and high compressibility render it a very weak and problematic soil for building. Using the analytic hierarchy process, Paul *et al.* (2022) studied peat from five sites in North-Eastern Region for utilisation in the energy industry. The analytical results and the significant calorific values of their peat samples present immense prospects for peat as an energy source.

Das *et al.* (2022) applied geochemical proxies to peat from Ziro Valley in Eastern Himalaya, Arunachal Pradesh, to study palaeoclimatic variations and to reconstruct the palaeoenvironmental conditions. The geochemical records suggest that the peat was accumulated under ombrotrophic and minerotrophic conditions in a moist subtropical environment.

THE SCOPE FOR RESEARCH ON PEAT AND PEATLANDS IN INDIA

The majority of literature identified for this review reports on palaeoenvironmental studies. Across the four regions where we identified previous research that involved peat, there is generally some information on peatland type, peat-forming vegetation, peat properties, climatic conditions and/or depositional settings although it is often limited and sporadic. Information on energy potential, carbon storage and emissions is lacking except for results from a recent limited study in North-Eastern Region.

Detailed data on peat thickness and how it varies across regions is also largely absent, making accurate assessments of carbon reserves and energy potential difficult. Systematic mapping by soil survey agencies is limited, and remote sensing techniques that connect vegetation types with peat depth have rarely been employed. These gaps highlight the need for extensive field surveys and remote sensing studies to accurately assess both undisturbed and human-altered peatlands.

For this article we have compiled spatial data for peat deposits, located from previous publications reporting mainly palaeoecological research, into a single map. However, the existing literature on palaeoclimate studies is scarce, relying mainly on palynological data and radiocarbon dating. The organic petrological and geochemical characteristics of peat have hardly been explored. Trace element analysis of peat deposits could provide crucial insights into palaeoenvironmental and palaeoclimatic conditions, and this is a research area that does not currently focus on Indian peatlands.

Various methods (e.g., Hg stable isotope; $\delta^{15}N$; ^{13}C-NMR; biomarker study by GC-MS; Py-GC-MS; IR-MS; SEM; TEM; FT-IR; UV/Vis spectra; gravimetric moisture determination; TGA; nutrient analyses by ICP-MS; trace elements; CO_2 and CH_4 emissions measured by Los Gatos ultraportable greenhouse gas analyser; statistical analysis) have been applied extensively and globally to study peat for various applications (e.g., as fuel, for manufacturing active carbon and soil-improving media for horticulture and agriculture, etc.) and peatlands for various purposes (e.g., as fuel resource, flood regulator or wildlife habitat, to assess palaeodepositional settings, palaeoclimate variability, carbon storage, greenhouse gas emission, etc.). However, such investigations are notably lacking or limited in Indian peatlands so far.

Although India is a vast country with many rivers and lakes, and its climate is often humid across many broad swathes of land, the mires that play important roles in water regulation, biodiversity and carbon storage have not been inventoried and remain largely unmapped. The lack of mapping poses significant challenges for conservation, sustainable land use and climate change mitigation. Resolving this issue demands collaboration among various agencies such as soil survey organisations, forestry departments, research institutions and remote sensing specialists, to produce the detailed maps and data that are essential for effective peatland management. Without a comprehensive understanding of the distribution and characteristics of mires and other peatlands, assessing their ecological value and implementing effective policies to protect them from threats like urbanisation, drought, pollution and agricultural expansion becomes a significant challenge. Therefore, mapping Indian mires and peatlands is essential not only for preserving biodiversity but also for maintaining ecological balance and supporting livelihoods that depend on these fragile ecosystems.

As peatlands perform critical ecological functions such as carbon sequestration, water regulation and biodiversity conservation, it is essential to compile a comprehensive inventory of all mires and peatlands. This inventory should document key characteristics including the geographic location and type of peatland (e.g., bog or fen), the extent of surface outcropping, thickness of the peat deposit and peat properties. Achieving this would require a combination of approaches: ground surveys and coring to determine peat thickness and composition; remote sensing and aerial imagery to map vegetation patterns and peatland extent; and integration of historical land-use data and GIS-based analyses to assess changes over time and anthropogenic impacts. Such data will provide a foundation for sustainable management, ensuring that peat extraction is balanced with the need to preserve these ecosystems' environmental and climatic roles. Moreover, this inventory will support decision making for land-use planning, climate change mitigation strategies and conservation efforts, helping to protect peatlands from overexploitation and degradation.

Furthermore, peatlands that have been covered by younger sediments are often overlooked. These buried peat deposits are significant not only for their potential as a resource but also for the valuable environmental and climatic records they hold - which can offer insights into past ecosystems, climate changes and carbon cycles. Identifying and mapping such peat requires advanced techniques, such as drilling and remote sensing, to assess their extent, depth, and quality. Although remote sensing might have limited direct use for peat characterisation, it is useful for creating conceptual models of river avulsions and identifying regions of subsidence and uplift. These insights will assist with inferring potential peat-forming zones and understanding landscape evolution.

This overview highlights the promising scope for studying Indian peatlands to enhance understanding of palaeoclimatic patterns, palaeoenvironmental conditions, extent and environmental services of mires and peatlands, and the potential for utilisation of peat in energy, agriculture, horticulture or other sectors.

CONCLUSIONS AND RECOMMENDATIONS

- Only a few peatlands in India have been studied, and then only sparingly in terms of their genesis and depositional conditions. Information about peatland type, peat-forming vegetation, peat properties, energy potential, carbon storage and potential emissions are either completely missing or these aspects have rarely been studied anywhere on the sub-continent.
- Systematic mapping by soil survey agencies has been limited, and remote sensing techniques that connect vegetation types with peat depth have seldom (if ever) been employed. Thus, there are notable gaps in knowledge about the extent and status of peatlands and peat reserves in India.
- In some parts of the globe, peat has been viewed as an important fossil fuel. Indeed, as a fossil resource, peat has found diverse applications including use (after mining) as both an energy source and a raw material for horticultural growing media and other products, as well as in situ for peatland agriculture. Increasingly across the world, however, more-sustainable alternatives for all consumptive uses of peat are being developed so that peatlands can be reserved for carbon, water supply and biodiversity services.
- Peatlands nowadays attract significant worldwide attention due to the increasing CO_2 levels in the atmosphere that are considered responsible for global warming. Peat is rich in carbon sequestered from the atmosphere, and its retention in peatlands is a viable nature-based option for lowering greenhouse gas emissions, as well as for compensating unavoidable emissions via carbon credits schemes.
- Without detailed spatial data on peat extent and thickness, it is difficult if not impossible to arrive at accurate estimates of peat carbon stocks. Thus, a detailed study of peat and peatlands of India is essential, as understanding these resources is key to promoting efficient and sustainable utilisation.
- In relation to the increasingly urgent climate and energy considerations, the information gaps we have discovered highlight the need for extensive field and remote sensing surveys to accurately record both undisturbed and human-altered peatlands. Baseline knowledge is indispensable for enabling informed decision-making regarding their management, utilisation and potential role in meeting international carbon-balance obligations.
- India lacks comprehensive mapping and inventory for its mires and peatlands, and this represents a key area for future research. A comprehensive inventory of peat reserves and peatlands is essential for understanding their location, size, quantitative and qualitative characteristics, and overall distribution.
- Peat and peatlands research in India could benefit carbon storage and climate regulation bodies, water storage and supply organisations, biodiversity conservation agencies, fish farming, flood control and prevention agencies, and the energy sector as well.

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AUTHOR CONTRIBUTIONS

AK: conceptualisation, data curation, literature review, investigation, writing original draft, review and editing of manuscript; KC and PKS: conceptualisation, supervision, review and editing of manuscript.

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Author for correspondence: Professor Dr Prakash K. Singh, MP Singh Lab of Coal and Organic Petrology, Department of Geology, Banaras Hindu University, Varanasi, 221005, India
Tel: +91 9935819700; E-mail: prakashbhu@rediffmail.com