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REVIEW ARTICLE

Sunn hemp - An under-exploited versatile crop for soil nitrogen transformation and fibre production

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Abstract

Sunn hemp (*Crotalaria juncea* L.) is a versatile legume belonging to the family Fabaceae, commonly used as a green manure or cover crop adding benefits to the cropping system. Nowadays, the excessive use of chemical sources of nitrogen to meet the crop demands has led to poor nitrogen use efficiency and significant environmental degradation. Reducing the use of synthetic fertilizers by supplementing them with green manure can minimize these negative impacts without compromising crop requirements. The incorporation of sunn hemp helps to improve the soil structure, water holding capacity, problem soil reclamation and increases nitrogen availability to the succeeding crop. Besides being used as a green manure crop, it is also grown as a fibre crop, due to the soft, strong and slightly lignified nature of its fibre. Synthetic fibres in blends are deleterious to the planet, requiring the search for natural and sustainable alternatives. The value of ecologically friendly resources has been increasing. Sunn hemp fibre is an underutilized lignocellulose fibre with a wide range of applications and an excellent substitute for synthetic fibres as it has natural characteristics such as high mechanical strength, low density, low cost, easy availability, biodegradability, etc. It is a fast-growing legume with high biomass, increased accumulation of nitrogen, weed suppressor, nematode controller and generates bioproducts *viz.,* biofuel and bioenergy. The role of sunn hemp in nitrogen mineralization, their fibre properties and versatility in day-to-day activity make it a promising crop for the present and future generations. This review article presents the various uses of sunn hemp through past years of research.

Keywords: alternative fibre; biodegradable; bioproducts; soil improvement; versatility

Introduction

Sunn hemp (*Crotalaria juncea* L.) is a tropical premier legume and foreign exchange earner till 1960s generally grown as a cover crop / green manure, due to its soil improvement benefits towards global cropping system. In India, it is also cultivated for fibre and green fodder. It is a fast-growing shrub that produces a significant dry biomass of roughly 2268 kg acre^{-1} over a short period of 9-12 weeks, resulting in a worldwide production of 130000 MT year^{-1}(1). Globally, sunn hemp ranks first in area (27 %) and the production (23 %) in India. Sunn hemp fibres are dull white, durable and strong. It is primarily grown in Odisha, Uttar Pradesh, Bihar, Chhattisgarh, Madhya Pradesh, Rajasthan, Tamil Nadu and Maharashtra. In India, it is cultivated over an area of 9040 hectares producing 40270 bales (1 bale = 180 kg) with an average productivity of 810 kg ha^{-1} (2).

Meeting crop nitrogen (N) demand from organic nitrogen (N) sources could be one among the most important challenges in building sustainable agricultural systems. Crops are predicted to remove approximately 38 million tons of nitrogen from the soil in India each year, which must be substituted through green manure and other biological nitrogen-fixing activities (3). Green manure crops switch atmospheric nitrogen into plant-usable forms (e.g., NH_4^+, NO_3^-) by biological nitrogen fixation (4). Leguminous cover crops, such as sunn hemp can satisfy nitrogen demands for a variety of crops (5, 6). Sunn hemp incorporation at 50-60 days generates 15 tons of green matter, resulting in an average of 50-75 kg of N, 15-20 kg of P_2O_5 and 40-65 kg of K_2O ha^{-1} (7). In addition, root nodules add 50-60 kg of nitrogen. They are utilized to supply and scavenge nitrogen in the soil for future crops. These cover crops have been shown to improve yield and quality in various vegetable crops in South Florida by enhancing plant growth and contributing to soil incorporation (8).

At the beginning of the 21st century, interest in sunn hemp grew due to its environmental friendliness and biodegradability compared to synthetic fibres. Sunn hemp is an alternative to synthetic fibres due to the rising need for ecologically acceptable materials that can be blended with natural fibres. Synthetic fibres used in composites, such as

Kevlar, glass fibres, aramid and nylon are manmade and pose environmental risks. When burned they release hazardous substances such as CO and smoke, are non-biodegradable, difficult to dispose of and negatively impact both water and air quality (9, 10). This approach utilizes biodegradable, reinforced green composites derived from plant fibres. Natural fibres offer significant environmental advantages over synthetic fibres due to their desirable properties, including affordability, low density, high mechanical strength, ease of availability and processing, environmental friendliness, non-corrosive-ness, abundance, biodegradability, renewability, non-toxicity and recyclability (11, 9).

Sunn hemp is primarily grown as a fibre crop around the world because of its soft, slightly lignified and robust fibre, which has traditionally been used to make ropes, strings, twines, floor mats and fishing nets (12). Sunn hemp fibre has a high cellulose content, low lignin content, high tensile strength, greater durability than jute and low ash content (13). It also gained significance due to the increasing demand for specific fibre quality required in the production of tissue paper and currency paper (14). The plant holds economic significance for several reasons, including its high biomass yield, weed suppression ability, resistance to various diseases and pests as a non-host, enhancement of soil organic matter, synergistic interactions and exceptional nitrogen-fixing capability in association with Rhizobacteria (15).

Current scenario of sunn hemp

To maintain food and nutritional security, the inclusion of legumes in today's cropping system offers benefits to the soil fertility (16). Sustainable agriculture could be attained by involving technologies that would result in increasing the nitrogen availability of the soil in which legumes particularly sunn hemp act as a key contributor to the ecological, environmental and economic sustainability of crop production and enhancing the resource use efficiency (17). Research has shown that the sunn hemp seed market reached USD 121.2 million in 2022 and is projected to grow to USD 194.93 million globally by 2030, with a Compound Annual Growth Rate (CAGR) of 6.3 % during the forecast period of 2023–2030 (18). Asia-Pacific crop production systems hold the largest share of sunn hemp seed market, supported by the region's substantial livestock industry. Sunn hemp fodder is gaining attention as a high-protein source for livestock. The crop's performance in nonconventional sectors such as biofuel, paper, pulp and packaging industries further enhances its versatility (19). Notably, clean biofuel with a maximum yield of 91.3 % has been obtained from sunn hemp seeds using a KOH catalyst over a four-hour reaction time with an oil-to-methanol molar ratio of 1:11 (20). Due to its ease in recycling, degrading and composting features, it is an alternative for petroleum-based products in pulp and packaging industries (21). The role of sunn hemp in day-to-day life is replaceable.

Role of sunn hemp residues on nutrient mineralization

Decomposition is one of the most significant processes associated with nutrient cycling and generation of soil organic matter. Nutrient cycling is a key process in an ecosystem that is directly involved in crop productivity. Cover crops or green manures are focused mainly on conservation agriculture as they cover the soil and enhance the availability of nutrients after the mineralization process in the global cropping system (22). Green manure obtained from *C. juncea* improves soil quality by enhancing physical properties such as aggregate stability (23). Crop residues play a vital role in agriculture by managing waste in an environmentally responsible manner and increasing soil organic matter (24). They contribute significantly to plant-soil interactions, helping to incorporate plant nutrients into the soil. After carbon, nitrogen is the most important nutrient influencing soil productivity (25). The nitrogen decomposition corresponds to residual breakdown. The breakdown of litter is essential for soil structure preservation as the nutrients associated with the litter will be released for recirculation and stabilize the environment. Among the factors, residual quality and soil properties determine the decomposition rate. The rate of decomposition often regulates the rate at which nutrients are released from litter (26). During the first week of sunn hemp incorporation, the residues underwent decomposition, releasing 50-75 % of their carbon and 65-75 % of their nitrogen, which led to a 20-94 % increase in extractable soil NO_3-N (4, 27). The majority of N in the labile portions of the plant, such as leaves and flowers, decomposes rapidly at first, leaving behind recalcitrant tissues, or stems, which are resistant to decomposition due to their low N content and high levels of complex carbon compounds such as lignin. As a result, nitrogen release rates decline during the later stages of mineralization (28, 29). Different plant species exhibit varying decomposition rates; legumes have a lower C: N ratio compared to other C4 species (30). Sunn hemp has a C : N ratio of 18.9:1 that favours the growth of bacterial population (5, 31, 32). Sunn hemp amendments increase soil nutrient levels, organic matter and cation exchange activity when added to the soil, especially in low-organic matter soils (5, 33). It can produce more than 2268 kg of biomass and fix > 45 kg of nitrogen/acre with 50 % N available to the cash crop (34, 35). Based on the atmospheric conditions, the mineralization rate and dry weight of the crop will differ. In a tropical climate, sunn hemp organic matter decomposes in approximately two weeks, suggesting that the maximum rate of nitrogen mineralization occurs during this period (36). It has produced 10.5 t ha^{-1} dry weight (DW) in winter and 25 % less DW in summer because of its best in terms of short days (33). Research has shown that sunn hemp manuring could be an essential component in integrated nutrient management (INM) for several crops grown in the late summer or during the rainy season (kharif) to supply roughly 50 % of the crop's nitrogen needs (37). According to an earlier study, the N content of sunn hemp manure increased rapidly during the first 30 days and then gradually declined (38). Generally, after 30-50 days of green manure decomposition, nitrate and nitrite together account for more than 70 % of the extractable inorganic nitrogen. In the initial 20 days, the proportion of ammonium-N remains comparatively higher, ranging from 45 % to 48 %. A 30-day decomposition period of green manure with a C: N ratio of 14:1 has been identified as the most efficient chemical indicator of nitrogen release (39, 40). At 10, 20, 30, 40 and 50 days, the available N content in the soil matrix was 62.71, 92.27, 91.46, 46.29 and 36.58 kg/ha, respectively. Based on the fibrous status of the plant, nutrient release and dry matter will vary (41). Among legumes, the more fibrous crops like sunn hemp (99.0 d) and pigeon pea (130.8 d) have more half-time than less fibrous crops like dwarf *Mucuna* (70.7 d) and jack bean (60.8 d). Increased lignin, cellulose and polyphenols will lead to slower decomposition rate so that it can be able to protect the soil against erosion besides contributing to soil organic matter (42).

Quality of sunn hemp fibre

Sunn hemp fibre is an under-exploited lignocellulose fibre with a unique potential in various fields and an ideal substitute for synthetic. It is coarse, stiff, strong and lustrous, with a whitish, grey, or yellow colour and is as dense as hemp but tougher than jute fibre. Fibre quality depends on the age/ stage and retting conditions (19). The stems contain about 40 % fibre, which has greater tensile strength and is more durable under exposure than jute. The fibre is superior to jute as it is stronger, more lustrous and more resistant to environmental deterioration (43). It has cellulose and pentosan as a major constituent. It has 67.8 % of cellulose, 16.6 % of hemicellulose, 0.3 % of pectin, 3.5 % of lignin, 0.4 % of fat and wax, 1.4 % of water-soluble substance and 10 % moisture (44).

The main characteristics that are used to assess the sunn hemp fibre qualities are strength, color, length, fineness, tangling, lusture, texture and amount of refraction, including dirt and sticks (45). Other fibre qualities include extensibility, torsional rigidity, fineness and density (46). The length to breadth ratio of sunn hemp is 450, which is comparatively higher than that of jute, daincha, mesta, banana, arecanut and manila hemp, indicating its finer fibre quality (47). One study reported the fineness, fibre length and bundle strength of compost treated sunn hemp stalks as 10.8 denier, 32.34 cm and 11.1 g/tex respectively (48). Thus, it is evident that sunn hemp is more than just a nitrogen-fixing plant; it also holds potential to produce value-added products (49, 21). The properties of sunn hemp fibre are given in the Table 1.

Economic value of sunn hemp fibre

In recent years, the use of natural fibres has surpassed that of synthetic fibres due to their cost-effectiveness, eco-friendliness, easily availability and biodegradability. The environmental impact of synthetic fibre production is estimated to be three times greater than that of natural fibre production. The carbon footprint of bast fibre is 20-350 % lower than that of synthetic fibres (50). Sunn hemp fibre is also used in car components and has been tested as a replacement for cement when combined with fly ash in concrete (51). Its high cellulose and low lignin content make it a highly promising raw material to produce tissue paper and currency notes, as well as handcrafted paper, twine, ropes and fishing nets (52-54).

Why sunn hemp is an alternative to synthetic fibre?

- The low density of sunn hemp fibre makes it a viable alternative to synthetic fibres for lightweight applications (55, 56).
- Sunn hemp, due to its low wax content can serve as a replacement for synthetic materials in composites (47, 57).
- The crystallinity index influences the mechanical properties of natural fibre composites (58).
- The high thermal stability of the fibre makes it suitable for composite reinforcements (59, 60).

Table 1. Properties of sunn hemp fibre (46).

S No	Forms of fibre	Property	Measurement
1.	Ultimate cell	Length (mm)	5 - 20
		Breadth (10^{-3} mm)	12 - 35
		Length/Breadth (L/B)	450
2.	Filaments	Gravimetric fineness (tex)	5.5 - 17.0
		Tenacity (g/tex)	30 - 40
		Module of Torsional rigidity (10^{10} × dynes cm^{-2})	1 - 2
		Extension at break (%)	2.5 - 3.5
		Flexural rigidity (dynes cm^{-2})	125 - 175
3.	Bundle	Transverse swelling in water (%)	18 - 20
		Tenacity (g tex^{-1})	15 - 35
		True density	1.53
		Apparent density	1.34
		Moisture regains (%) at 65 % relative humidity	10.5
		Moisture regains (%) at 100 % relative humidity	28.5

- It can also be utilized for hygiene and food packaging (61).

Overall qualities of sunn hemp fibres reveal the possibility of using them in numerous industries and as an intriguing alternative to synthetically produced fibres in composites and other purposes (58).

Multiple roles of sunn hemp

More recently, interest in sunn hemp has grown due to its recognition as a valuable inter-crop, cover crop or green manure for nematode (biofumigation) and weed control, as well as a source of fodder or forage for livestock, biofuel and pharmaceutical applications.

Increased production in crop rotation

Presently, it is used worldwide as a cover crop, green manure, or forage. The use of sunn hemp in crop rotation has effectively increased crop production (Table 2).

Table 2. Crop rotation with sunn hemp.

Rotation with crops	Percentage of yield increase	References
Soyabean	6	30
Spring corn	70	91
Grain sorghum	10.6 bu/a (269.24 kg/acre)	92
Wheat	2.3 bu/a (58.42 kg/acre)	92
Strawberry	52	27
Tomato	71 - 85 t/ha	93
Green corn	5 (Sunn hemp + lupine)	94
Cabbage	19 (Sunn hemp + lupine)	94

Weed suppression and allelopathy

The allelopathic activity of sunn hemp had a significant effect on the neighbouring plants. Research suggests that the growth stages of sunn hemp are an important factor in effective weed control (62). The incorporation of sunn hemp has been shown to significantly reduce weed populations, decreasing weed intensity in *Vicia villosa* by 74 % (63). Ground-dried residues of sunn hemp (3 days after planting) reduced the germination of *Eleusine indica* and *Amaranthus blitum* by 80 % and 61% respectively (64).

Nematicidal activity

Sunn hemp can improve soil fertility and serves as a potential alternative for effectively managing plant-parasitic nematodes while also promoting the population of free-living nematodes (36). Furthermore, an increase in free-living nematodes extends the decomposition period, likely due to their role in enhancing the breakdown of soil organic matter and increasing the availability of phosphorus and nitrogen, ultimately supporting nematode population growth. The list of controlled nematode species is provided in the Table 3.

Table 3. Nematicidal activity of sunn hemp.

Nematodes controlled	References
Root-knot nematode (*Meloidogyne spp.*)	95, 31
Sting nematode (*Belonolaimus longicaudatus)*	96
Helicotylenchus	97
Reniform nematode (*Rotylenchulus reniformis*)	6, 98
Meloidogyne javanica	99
Meloidogyne incognita	98
Xiphinema spp.	98
Burrowing nematode (*Radopholus similis*)	100

Biofuel production

Global projections indicate that the biofuel industry will supply 22-30 % of the transport sector's needs between 2050-2060 (65). By 2030, the revised RED-II and the green deal in the EU aim to increase the share of advanced biofuels to 3.5 % and reduce greenhouse gas emissions by 50 %, partly by allocating the 100 M ha area for biofuel feedstock production. Sunn hemp biomass can be converted into a range of bioenergy products, including bioethanol, bioplastics, biodiesel as well as paper, building materials, absorbent materials and automotive components (53, 59). Biodiesel extracted from the sunn hemp seeds with some modifications has shown high water content and effective carbon capture and reuse (CCR) owing to its favourable H/C molar ratio and low sulphur content (66, 67). A field trial reported that an average dry biomass yield of 11 Mg ha^{-1} produced an energy yield of approximately 200 GJ/ha (68).

Packaging industry

Generally, molded pulps can be obtained from recycled paper, wood and non-wood products. The wood products and recycled papers have led to deforestation and forest ecological activity losses causing environmental imbalance (69). In the case of non-wood sources, molded pulp derived from sunn hemp stems can be used as a substitute for fibrous raw materials in packaging the products, as it possesses eco-friendly, recyclable and biodegradable properties (21). Therefore, it is increasingly being used in packaging logistics as an alternative to plastic, solid wood and paper-based materials (70).

Tissue paper, cigarette paper and currency production

As sunn hemp contains a maximum of 78 % cellulose, it is often used as a traditional raw material for making premium quality tissue paper, fine quality cigarettes and currency notes (13, 71). Due to the high cellulose and low lignin content of its fibers, sunn hemp is an excellent source of raw material for the pulp, paper and specialty paper industries (19). The presence of hemicellulose regulates the hydrogen bond formation, which in turn contributes to desirable paper properties (72, 21). Sunn hemp fibres are also used in currency production in countries such as India and Brazil (52, 46, 73).

Medicinal properties of sunn hemp

The production of synthetic drugs to cut down disease-causing microorganisms was practiced worldwide (74). However, it causes harmful complications in human organs due to its excessive use (75). To overcome the side effects and limitations, researchers have focused on medicinal plants as alternatives because of their antioxidant, antidiabetic, antiarthritic, antipyretic, anti-inflammatory and gastrointestinal properties (76, 77). Sunn hemp seeds have been used in the treatment of psoriasis (78).

Toxicology facts of sunn hemp

The discussion of toxicity in sunn hemp was due to the presence of pyrrolizidine alkaloids present in the *Crotalaria* species. An earlier study concluded that various research has identified sunn hemp as a valuable forage crop without any toxic effects (79). In Florida, due to the presence of low levels of pyrrolizidine alkaloid in sunn hemp seeds, it is excluded from livestock diets after the formation of seedpods as it can cause acute toxicity leading to weight loss (80, 81). These alkaloids are also present in small amounts in leaves and stems. The variety 'Tropic Sun' is considered non-toxic to both livestock and poultry (35). Pyrrolizidine alkaloids like senecionine, reddelline, seneciphylline, junceine and trichodesmine were present in the crotalaria species (82). The main pyrrolizidine alkaloids in the seeds of *C. juncea* were trichodesmine and junceine (83). Research indicates that based on the size of the leaves, the proportion of alkaloid concentration will vary as the intact leaves show higher trichodesmine concentration and the comminuted leaves have higher monocrotaline concentration (84). Studies have shown that trichodesmine poisoning occurs in both horses and pigs from these earlier strains. An earlier study suggested that soaking the sunn hemp seeds in hot water for 24 hrs at 60 °C reduced the toxic content of alkaloids by 52.21 % (85). Reducing anti-nutritional factors to safe levels makes sunn hemp a viable substitute protein source for both humans and livestock (19).

Importance of sunn hemp in relation to climate change

Evidence of turbulent climatic changes has been noticed worldwide. Agriculture is both a contributor to and a victim of climate change. For example, rice straw is often burned due to its slower decomposition rate due to its high lignin content, high C: N ratio and poor residual quality-practices that contribute significantly to green-house gas emissions (86, 38). The carbon footprint evaluation for sunn hemp is 423 kg CO_2 eq./tonne of fibre (38). Each year, around half of the rice straw is burned, the remaining portion is either left unprocessed for landfill decomposition or utilized as fodder or in the production of wood composites (87). Conservation agriculture practices of incorporating sunn hemp have given 8-10 quintals of biomass on a dry weight basis added to the soil that provided nutrients (150-210 kg/ha of N) by conserving soil and water which has been beneficial for the succeeding crops (88). As a soil amendment, sunn hemp incorporation reported a positive effect on soil becoming more pulverous and increasing porosity and its biomass improves the dry aggregate soil stability (89). Being a cover crop, sunn hemp increases soil organic carbon by 7 % and reduces CO_2 emission by 18 %, considered an important tool for potential global warming mitigation (49). Research reported that mixing rice straw with tender sunn hemp accelerated decomposition, helped minimize large-scale residue burning and contributed to a pollution-free environment while supplying nutrients to nutrient-deficient soil (90).

Conclusion

The excessive consumption of chemical sources can be minimized without compromising crop nutrient require-ments by incorporating sunn hemp into the soil. In addition to improving soil fertility, sunn hemp also serves as a fibre crop and a sustainable alternative to synthetic fibres. As an under-exploited lignocellulose fibre source, sunn hemp has enormous potential due to its high biomass production and significant nutrient accumulation, contributing approximately 130-134 kg N ha^{-1}. Its leaf extracts act as weed suppressor, non-host to many pests and pathogens, functions as a nematode controller and possesses medicinal properties. Furthermore, sunn hemp is valuable for biofuel production and plays a role in post-harvest applications such as packing materials, chemicals and bioproducts including tissue paper, cigarette paper and currency. Overall, the properties of sunn hemp demonstrate its potential for use in numerous fields throughout its growth stages, from seed to residue, benefiting farming communities and industries and making it a versatile crop for present and future generations.

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Authors' contributions

VPH collected the articles and drafted the review paper. KS contributed to writing, supervision, editing and making corrections to the manuscript. SE, RA, KM, TSD and PA assisted in revising and summarizing the manuscript.

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