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Deciphering the mystic potentials of wild indigo (*Tephrosia spp*.) in agro arid ecosystems

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Abstract
Tephrosia, a genus of flowering plants, has long intrigued researchers for its potential applications in dry ecological settings. Contemporary agriculture confronts formidable challenges, including land degradation and soil fertility depletion, exacerbated by the excessive use of inorganic fertilizers. While inorganic fertilizers have bolstered food grain production, they have concurrently compromised soil health, microbial diversity, and water retention capacity. This predicament necessitates a shift towards organic fertilizers to foster robust crop growth and sustainable agricultural practices. Organic fertilizers, particularly green manures, offer a holistic solution by replenishing soil fertility, enhancing microbial activity, and improving soil physico-chemical properties. Among green manures, *Tephrosia* emerges as a paramount choice due to its nitrogen-fixing ability, medicinal attributes, and adaptability to challenging environments. This review delves into the latent potential of *Tephrosia* as a green manure crop, highlighting its role in soil rejuvenation, weed control, and pest management. Furthermore, it elucidates *Tephrosia*'s efficacy in mitigating soil salinization, enhancing nutrient availability, and fostering soil structure. By unravelling the enigmatic capacities of *Tephrosia*, this article advocates for its widespread adoption in sustainable agriculture, heralding a paradigm shift towards ecological resilience and quality food grain production. This review endeavours to elucidate the mystique surrounding *Tephrosia* by examining its ecological significance, physiological adaptations, and potential roles in arid environments. Through a comprehensive analysis of existing literature, this paper aims to provide insights into the multifaceted dimensions of *Tephrosia*'s contributions to dry ecology, including its role in soil stabilization, biodiversity conservation, and medicinal properties. By deciphering the enigmatic potentials of *Tephrosia*, this review seeks to foster a deeper understanding of its relevance in sustainable ecosystem management and the development of innovative solutions for arid land restoration.

Keywords: Green manures, soil health, organic matter, nitrogen fixation, drought resistance

Introduction
The current state of agriculture is marked by significant challenges, including land degradation and declining soil fertility, prompting an excessive reliance on inorganic fertilizers (Gomiero, 2016) [15]. While these fertilizers have boosted food grain production, they have simultaneously eroded soil health, diminished microbial diversity, and compromised water retention capacity, exacerbating issues such as soil salinization. This degradation underscores the imperative for organic fertilizers, which nurture robust crop growth by fostering healthy, living soil. Given the obstacle of intensive agriculture in fragmented land holdings, organic fertilizers emerge as a pivotal solution for sustaining agricultural production (Singh, 2012). These fertilizers facilitate soil fertility restoration through balanced nutrient recycling and the stimulation of beneficial microorganisms, thereby improving soil physico-chemical conditions and micronutrient availability. Moreover, they enhance soil aggregation, water infiltration, and water holding capacity, thereby increasing water and nutrient use efficiency. Organic fertilizers also demonstrate potential in weed and soil-borne pathogen control, disrupting insect pest lifecycles, and augmenting soil organic matter content, ultimately fostering sustainable agricultural productivity and ensuring the production of quality food grains (Griffin and Garren, 1976; Witt *et al*., 2018; Varma *et al*., 2017) [17, 61].

An effective method of applying organic fertilizers involves incorporating green manure into the soil. Green manures refer to crops grown specifically for soil improvement, which are then ploughed back into the soil upon reaching the flowering stage. The primary objective of incorporating green manure is manifold: it enhances soil organic matter, enriches soil nitrogen content, boosts soil humus levels, mitigates soil erosion, enhances soil aeration, and improves water retention capacity (Ahmed *et al*., 2020) [3]. Furthermore, it optimizes various physical and chemical parameters of the soil, such as electrical conductivity (EC), while reducing nutrient loss through leaching. Green manure acts as a natural cover, suppressing weed growth, and contributes to soil pH regulation through acidification. Additionally, it serves as forage for beneficial pollinating insects and facilitates the upward movement of nutrients from deeper soil layers, benefiting shallow-rooted crops (Vakeesan *et al*., 2008) [59]. By addressing these aspects, green manure incorporation bolsters soil fertility, reclaims problematic soils, and fosters conditions conducive to sustainable cultivation practices (Vijayaraghavan and Ramachandran, 1989; Verma *et al*., 2023 and Prajapati *et al*., 2023) [63, 62, 42].

In the realm of green manure crops, both legumes and non-legume grasses find common application. Legume crops, in particular, are widely favoured for their symbiotic relationship with nitrogen-fixing bacteria, which enhances soil nitrogen availability and reduces reliance on synthetic nitrogen fertilizers (Abd-Alla *et al*., 2023) [1]. Additionally, legume green manures serve as a vital source of essential nutrients for subsequent crops (Bhuiyan and Zaman, 1996) [8]. Among the array of legume green manure options, the *Tephrosia* genus occupies a paramount position, especially in single-cropped wetland and saline-sodic conditions. *Tephrosia* exhibits unique characteristics such as lowering soil pH and mitigating soil salinization. It has the capacity to accumulate significant amounts of nitrogen, ranging from 70 to 115 kg/ha, and has been recognized since ancient times for its medicinal and insecticidal properties (Wortmann and Kaizzi, 2000) [65]. Despite its widespread distribution across pantropical regions, *Tephrosia* faces challenges due to its hard seed coat, resulting in physical seed dormancy that necessitates scarification before sowing (Ezenwa, 1999 and Shelton, 1994) [12, 55]. This review aims to delve into the hidden and underexplored potentials of *Tephrosia* as a legume green manure crop, shedding light on its role in fostering sustainable agricultural production.

Origin and Distribution

Tephrosia purpurea a member of the Fabaceae family, boasts a pantropical distribution and is extensively cultivated as a green manure crop worldwide. Its origins trace back to the Indian subcontinent and China. Within India and Sri Lanka, *Tephrosia purpurea* thrives as a ubiquitous wasteland weed. This erect, short-lived legume species exhibits a preference for dry, gravelly, rocky, and sandy soils, although it also demonstrates adaptability to loamy soils and tolerance towards saline-sodic conditions. Its habitat ranges from grassy fields, waste areas, and thickets to ridges and roadsides. Remarkably, it even thrives in coastal regions and the most arid, barren wastelands. *Tephrosia purpurea* showcases a remarkable altitude tolerance, flourishing at altitudes as low as 400 meters above sea level, with some instances of successful growth recorded at altitudes up to 1300 meters (Ramalingam *et al*., 2021) [43].

Ecological requirements

The optimal environmental conditions for the growth of this crop entail a mean annual temperature ranging from 18 to 28 degrees Celsius, coupled with an average annual rainfall spanning from 700 to 2500 mm. *Tephrosia purpurea* displays remarkable adaptability to various soil types, thriving in sandy soils prevalent in coastal regions, as well as impoverished, eroded upland soils, loamy soils, and even mine spoils (Mathur, 2016) [27]. Its resilience extends to saline-sodic soil conditions, where it can still flourish. Notably, the crop exhibits tolerance to a pH range of 3.5 to 7, with acidic soils proving particularly conducive to its growth.

Tephrosia: As a green manure crop

The persistent issue of low crop yields over the years can be attributed to inadequate methods of soil management, indiscriminate adoption of agronomic practices, and misguided nutrient management. Additionally, the depletion of soil organic matter, limited use of bio-and organic-fertilizers, and poor overall management practices further contribute to decreased crop productivity. One effective approach to boosting productivity without compromising soil fertility is the application of organic manures, coupled with the incorporation of organic substances into deficient soils through green manuring (Ghanshyam *et al*., 2001) [14]. In the realm of sustainable farming, organic amendments and green manuring emerge as preferable alternatives to chemical fertilizers. Nitrogen, a crucial nutrient for crop growth, poses challenges in management. However, these challenges can be overcome by incorporating leguminous green manures into agricultural practices. Furthermore, the presence of organic carbon in the soil enhances microbial activity and improves overall soil fertility. To achieve successful crop establishment, prioritizing nutrient management through organic sources, particularly green manuring, is essential. This holistic approach ensures not only improved crop yields but also fosters long-term soil health and sustainability in farming practices (Ramanjaneyulu *et al*., 2021) [44].

Tephrosia, renowned for its dual role as both a green manure crop and a nitrogen-fixing legume, possesses several notable characteristics:

1. **Slow Growth and Non-Palatability:** *T. purpurea* serves as a slow-growing green manure crop, largely unaffected by grazing from cattle.
2. **Self-Sowing Capability:** When cultivated continuously for two to four seasons within the same field, *Tephrosia* becomes self-sown in subsequent years, eliminating the need for fresh sowing.
3. **Hardiness and Drought Resistance:** *T. purpurea* exhibits hardy traits and a remarkable resistance to drought, making it well-suited for utilization during summer fallows .

Incorporating *Tephrosia purpurea* into the soil as green manure augments humus content and fosters the formation of large, stable soil aggregates, ideal for supporting plant growth. This effect is attributed to the binding properties of humus. Even when planted in waste areas such as coal mines and calcite mine spoils, *Tephrosia* retains its nodulating ability and nitrogen-fixing capacity, thus aiding in the reclamation of problematic soils. In specific regions like India, it has been successfully utilized as a green manure crop on saline-sodic soils, effectively reducing soil salinity by lowering soil pH (Orwa *et al*., 2009) [36].

Nodulation pattern in *Tephrosia*

Nodulation in *Tephrosia* unfolds in a distinct pattern, offering insights into its growth and nitrogen-fixing capabilities (Ishizawa, 1972 and Skorpil *et al*., 2005) [19, 57]:

- **Onset and Location of Nodulation:** Nodulation commences approximately three weeks post-germination of *Tephrosia* seeds, with nodules predominantly situated along lateral roots throughout all growth stages.
- **Nodule Development:** Initially, nodules appear as small, round, whitish structures, evolving into corolloid formations upon maturity. Notably, nodules transition in colour to pink around the sixth week, marking the onset of active nitrogen fixation, a phase that persists for 6 to 7 weeks.
- **Peak Nodulation Period:** *Tephrosia* exhibits maximum nodulation, typically occurring after 12 to 13 weeks, coinciding with the pod development stage. At this juncture, an average of 31 nodules per 10 plants is observed.
- **Nodule Characteristics:** Fully developed nodules in *Tephrosia* measure between 8 to 12 mm and are relatively fewer in number. By the 17th week, nodules shed from the root system, indicating the culmination of their lifespan.
- **Optimal Time for incorporation:** The optimal time to plough *Tephrosia* tops into the soil is at the end of the 12-week mark. Inoculating *Tephrosia* seeds with freshly isolated Rhizobia strains significantly improves both growth and nodule weight.
- **Nodule maturation and detachment:** Fully mature nodules transition to brown due to the conversion of haemoglobin to meth-haemoglobin. Subsequently, nodules detach from the root system, typically occurring by the 17th week.

This comprehensive understanding of *Tephrosia*'s nodulation process, elucidated by Gage (2004) [13] underscores its potential as a nitrogen-fixing legume with implications for sustainable agricultural practices.

Tephrosia: As a cover crop

Tephrosia demonstrates versatile growth patterns, thriving across all seasons with optimal sowing occurring between March and April, particularly conducive for seed production. While adaptable to various soil types, sandy soils are considered most favourable for its cultivation. The recommended seed rate for *T. purpurea* is 15-20 kg/ha for green manure purposes and 10 kg/ha for seed production. Overcoming seed dormancy is essential, achieved through a sequential process involving soaking in concentrated sulfuric acid, thorough washing, and shade drying.

For green manure cultivation, seeds are broadcasted, while a spacing of 30 × 10 cm is recommended for seed production. Incorporation of green manure crops should occur within 60 days after sowing, while seed collection for seed purpose is ideal at 150 days after sowing. *T. purpurea* exhibits impressive biomass yields of 6-7 t/ha for green manure and seed yields ranging from 400-500 kg/ha.

Moreover, *Tephrosia* species serve multiple agricultural purposes, including as cover crops in rubber, oil palm, citrus, coffee, coconut, and tea plantations. Its dense foliage and strong root anchorage make it suitable for use as a windbreak, contour hedge, or shade plant. Intercropping T*ephrosia* with other crops such as maize or sorghum significantly boosts yields, as observed in various studies (Baligar and Fageria, 2007; Bosman and DeHaas, 1983; Munthali *et al*., 2014; Hagedorn *et al*., 1997) [5, 9, 31, 18].

Tephrosia: As a storage pest repellent

Tephrosia plants have long been recognized for their efficacy in protecting grains from weevils (Zhang *et al*., 2020) [66]. Dried leaves of *Tephrosia* possess potent insecticidal properties, particularly against bruchids, pests that commonly infest stored legume seeds in Southern Africa. In experiments conducted against *Sitophilus zeamais*, *Tephrosia* demonstrated significant insect mortality rates ranging from 85.0% to 93.7% within 21 days. The mean lethal exposure times (LT50) required for achieving 50% mortality varied depending on the concentration of *Tephrosia*, ranging from five to eight days.

Although the recommended dosage of dry plant materials for stored grains is typically around 5% (v/v), the actual application rates may vary due to differences in the content of active compounds among *Tephrosia* varieties or strains. Furthermore, the efficacy of *Tephrosia* against storage pests can vary based on the specific chemotype. For instance, exposure to *Tephrosia* chemotype 1, characterized by higher insecticidal activity, resulted in more rapid mortality among bruchids compared to chemotype 2, which exhibited lower activity (Zhang *et al*., 2020) [66].

The components within *Tephrosia* responsible for its insecticidal properties include deguelin, rotenone, sarcolobine, and toxicarol. Deguelin, though less toxic than rotenone, caused significantly higher mortality rates among pests. Meanwhile, tephrosin exhibited lower toxicity compared to deguelin, with an LC50 value calculated at 200 mg/kg. Obovatin 5-methyl ether, however, showed no significant difference in effectiveness compared to the control or extract from chemotype 2 plants (Zhang *et al*., 2020) [66].

Traditionally, *Tephrosia* leaves are harvested and dried in the shade, then ground into a powder and placed in grain storage containers to protect against pest infestation (Koona and Dorn, 2005) [23]. This method has been utilized effectively as a natural and sustainable approach to safeguarding stored grains from pests.

Tephrosia: As a forage crop

Tephrosia exhibits prolific seed production, leading to the accumulation of a substantial seed bank in the soil, allowing for self-sown crops in natural settings (Orwa *et al*., 2009) [36]. Its ability to remain green and succulent even during the dry season renders it an ideal fodder crop. The protein-rich leaves of *T. candida* make it a valuable fodder source for pigs and cattle. In terms of fodder yield, *T. candida* has demonstrated remarkable productivity, producing nearly 11 tonnes of dry matter per hectare during the first 7-month harvest, surpassing the growth of common fodder species like *Leucaena leucocephala* (Babayemi and Bamikole, 2006 and Mbomi *et al*., 2012) [4, 28].

However, the fodder value of *Tephrosia purpurea* presents conflicting reports. While it is utilized as fodder in India and South Africa before flowering, similar practices in Australia have been associated with livestock poisoning. This discrepancy underscores the importance of regional variations and proper management practices when considering *Tephrosia* as fodder (Orwa *et al*., 2009) [36].

Tephrosia: As a medicinal crop

Tephrosia purpurea, known in Ayurveda as Sarva vrana vishapaha, possesses a myriad of pharmacological properties attributed to its rich biochemical composition. Recent studies have revealed its diverse medicinal attributes, including antiulcer, antimicrobial, antibacterial, antiviral, anti-asthmatic, hepatoprotective, antihyperglycemic, antihyperlipidemic, immune-modulatory, antioxidant, wound healing, antiallergic, antileishmanial, anticarcinogenic, antifertility, antispermatogenic, anti-diarrheal, and diuretic properties. These pharmacological effects are attributed to various phytochemicals such as pongamol, purpurin, purpurenone, tephrosin, bulnesol, tephrostachin, β-sitosterol, among others, which have been isolated from *Tephrosia* (Saxena and Choubey, 1997; Soni *et al*., 2004; Kumar *et al*., 2007; Kavithe and Manoharan, 2006; Shah *et al*., 2010; Valli *et al*., 2011; Khan *et al*., 2021 and Nga *et al*., 2020) [51, 58, 60, 22, 34].

The whole plant is esteemed for its medicinal value and serves as a key component in herbal preparations like Tephroli and Yakrifti, traditionally used to treat liver disorders. *Tephrosia* exhibits acetylcholinesterase inhibitory action, contributing to the development of drugs for Alzheimer's, dementia, and other neurological disorders. Specific compounds such as tephrostachin are responsible for antiplasmodial activity, while tephrosin is credited with antiulcer properties. Additionally, compounds like quercetin, rutin, β-sitosterol, and lupeol confer anti-inflammatory and anti-cancer properties (Rao and Raju, 1979; Pelter *et al*., 1981; Pavana *et al*., 2007; Mohamed *et al*., 2009; Gopalakrishnan *et al*., 2010; Patel *et al*., 2010 and Samuel *et al*., 2019) [46, 41, 40, 29, 16, 38, 48].

Toxicological studies suggest that concentrations of up to 2,000 mg/kg are considered safe for *Tephrosia* consumption. The plant's bitterness, astringency, acridity, and thermogenic properties align with its traditional uses as an antihelminthic, antipyretic, and uterine tonic. *Tephrosia* has been utilized for centuries to alleviate cough, chest tightness, liver, spleen, and kidney enlargement, dyspepsia, chronic diarrhea, inflammation, skin disorders, elephantiasis, hemorrhoids, asthma, bronchitis, anemia, dysmenorrhea, chronic fever, boils, pimples, and gingivitis (Sangeetha and Krishnakumari, 2010; Khalafalah *et al*., 2010; Manjula *et al*., 2013; Mustak *et al*., 2012 and Bhardwaj and Verma, 2016) [49,21, 32, 62].

Studied the aqueous extract of *Tephrosia purpurea* on cardiovascular complications and cataract associated with streptozotocin-induced diabetes in rats. Their phytochemical investigations of *T. purpurea* revealed the presence of glycosides, rotenoids, isoflavones, flavanones, chalcones, flavanols, flavones, and sterols. The rich flavonoid content suggests that these components may be the main antidiabetic principles of the *Tephrosia* plant. Antioxidant mechanisms delay or prevent free radical formation, thus reducing life-threatening diseases. In Ayurvedic medicine, various parts of *Tephrosia* are used to treat diseases such as asthma, diarrhoea, jaundice, rheumatism, and kidney disorders. It is popularly known as 'Wild Indigo' and is distributed throughout India. It has also been reported to possess many pharmacological properties, including anti-inflammatory, wound healing, antiulcer, antimalarial, and antimicrobial effects. Padmapriya *et al*. (2017) [37] studied the antioxidant activity of various plant parts of *Tephrosia* and reported that the leaves extract showed effective cytotoxicity on colorectal cancer cells (IC50: 95.73 ± 9.6 µg/mL) and also had higher total phenolic (90.5 ± 6.7 µg/mg of gallic acid equivalent (GAE/mg)) and flavonoid content (21.8 ± 5.4 µg QE/mg). This could be attributed to the rich phenolic and flavonoid content in the leaves. Furthermore, the ethanolic extract of *Tephrosia* has exhibited anticancer activity against in vitro KB-cells culture (Saleem *et al*., 2001; Patil *et al*., 2011) [47, 39]. These diverse medicinal properties underscore the significant therapeutic potential of *Tephrosia purpurea* in traditional and modern medicine systems alike.

***Tephrosia*: Beyond its agricultural and medicinal applications:**

- **Fuelwood:** The wood of *Tephrosia purpurea* possesses an energy value of 14500 kj/kg and is collected for fuelwood purposes, particularly in northern India.
- **Poison:** *Tephrosia purpurea* exhibits toxic properties due to the presence of flavonoids like rotenone and deguelins (Tephrosin) (Ahmad *et al*., 1999; Chang *et al*., 2000 and Rao *et al*., 2020) [2, 10, 45], making it poisonous to fish. Pounded leaves have been traditionally used as a fish poison, containing up to 2.5% rutin, aiding in the fishing process.
- **Natural Dye:** Occasionally, *Tephrosia* leaves are utilized as a natural dye, producing orange-brown hues or, when combined with *Mucuna cyanosperman* Schumann, black dye.
- **Beverage:** In Indo-China, *Tephrosia* seeds serve as a substitute for coffee, offering an alternative beverage option (Sharma *et al*., 2013) [53].
- **Reclamating problematic soils:** *Tephrosia* species are adept at reclaiming degraded land, particularly when utilized as green manure on saline-sodic soils. Successful applications in regions like Rajasthan, India, have demonstrated its efficacy in reducing soil salinity and lowering pH levels (Duguma and Urga, 2023) [11].
- **Shade or shelter**: *Tephrosia* plants are cultivated as temporary shade crops in newly planted perennial crops such as citrus, coconut, coffee, rubber, and tea. This practice helps create favorable ambient conditions for the growth of cash crops.

Adverse impact of *Tephrosia*

Adverse impacts associated with *Tephrosia* species include their invasive tendencies when introduced to areas beyond their native range (Nelufule *et al*., 2024) [33]. This invasiveness is primarily due to their high adaptability to diverse environmental conditions and the longevity of their propagules, which can remain viable for more than a year. As a result, *Tephrosia* can outcompete native species, particularly through its shading effects, posing a threat to native tree species and leading to a reduction in overall biodiversity levels. This underscores the importance of carefully managing the introduction and spread of *Tephrosia* species to mitigate their negative ecological impacts.

Conclusion

In conclusion, *Tephrosia* presents a wealth of untapped potential beyond its role as a green manure crop. Despite its myriad benefits, it often remains underutilized and overlooked, relegated to wastelands and roadsides rather than integrated into mainstream agricultural practices. This oversight may stem from a lack of awareness among farmers regarding the crop's capabilities. However, *Tephrosia*, this roadside gem, offers numerous direct and indirect benefits to humans. From its ability to improve soil fertility as a green manure to its medicinal properties and ecological advantages, *Tephrosia* holds promise for sustainable agriculture and environmental conservation. To unlock the full potential of *Tephrosia*, it is imperative to raise awareness among farmers and promote its integration into agricultural systems. By shifting mindsets from solely focusing on crop cultivation to embracing integrated approaches that incorporate both crops and green manure, we can harness the concept of sustainable agricultural production. This concerted effort will not only enhance agricultural productivity but also improve the livelihoods of farmers while fostering environmental sustainability.

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