# Evaluation of Green Manuring with Sesbania aculeata on Nitrogen Economy in Cropping Systems

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## ABSTRACT
**Background:** Sesbania aculeata is a species of tree native to Africa and Asia commonly known as dhaincha or jantar. Due to its quick growth and ability to fix nitrogen biologically, Sesbania aculeata is crucial in crop rotations, especially in rice agriculture. Moreover, as prices of synthetic nitrogen fertilizers are increasing, the interest in the utilization of Sesbania aculeata is growing. The goal of the paper is to perform a literature review on the Sesbania aculeata's impact on biomass and nitrogen accumulation, its role as a nitrogen fertilizer substitute, the effectiveness of its utilization as a nitrogen resource, and on the yield of crops cultivated in rice-wheat, rice-rice and other cereal regimes.
**Sources of literature:** Evidence was drawn from Scopus, Web of Science, ScienceDirect, SpringerLink (Plant and Soil, Nutrient Cycling in Agroecosystems), PubMed Central, and regional agronomy journals, supplemented by AICRP-IFS and ICAR institutional reports, using keywords including “Sesbania aculeata,” “dhaincha,” “green manuring,” “nitrogen economy,” “nitrogen substitution,” and “rice-wheat cropping system.”
**Key observations:** Sesbania aculeata is shown to normally accumulate a high biomass (4.6-6 t ha -1 dry mass; up to 23 t ha 1 green mass) and fix 100-131 kg N ha -1, with biological nitrogen fixation accounting for 77-82 % of the total nitrogen in the plant, when grown for 45-60 days during the pre-rice or summer fallow period. The immediate rice crop used 43-122 kg urea-N ha -1 instead. The residual benefit in the following wheat crop was equivalent to 27-89 kg urea-N ha -1. The long-term integrated trials have shown the ability of Sesbania to maintain nitrogen-use efficiency gains and yields with 50% of the initial fertilizers used. Nevertheless, this conclusion is influenced by the age of the green manure used, the soil type, the greenhouse decomposition duration prior to transplanting, type of soil (the effectiveness of Sesbania green manure is lower in calcareous and some alkaline soils), the relative effectiveness of different traditional green manures and grain legumes as it has been shown in various studies.
**Research gaps:** There is still a lack of certain research areas such as the standardized reporting of biological nitrogen fixation efficiency, the evolution of soil nitrogen stocks over multi-decadal periods, farmers’ constraints in adopting new practices, and a relative economic analysis of this strategy against various nitrogen management alternatives.
**Conclusion:** Sesbania aculeata green manuring appears to be a proved method of increasing nitrogen performance in cereal-based cropping systems that can replace a significant share of fertilizer nitrogen. It should be kept in mind, though, that its implementation and efficacy depend on multiple factors such as soil type, degradation treatment, and other land use constraints available at the time of implementation of this measure.

**Keywords:** Sesbania aculeata; dhaincha; green manuring; nitrogen economy; biological nitrogen fixation; nitrogen-use efficiency; rice-wheat cropping system; fertilizer substitution

## 1. Introduction
For many decades now, green manuring—which is the practice of growing an quickly-growing crop (usually a legume) in order to add that biomass to the soil when it is still green—has been a key component of soil-fertility-management systems used by farmers throughout South Asia (Fageria *et al*., 2005; Ali *et al*., 2012) [1, 2]. Of the green manure species tested as potential cover-crops in cereal-based cropping systems, the species of green manure that has been the best-studied and best-researched species is the green manures that grow quickly, such as Sesbania aculeata (L.) Pers. (locally known as dhaincha in India and jantar in Pakistan) (Rahman *et al*., 2018; Beri *et al*., 1989; Beri *et al*., 1995) [3, 13, 14]. The major reasons for its popularity include the quick early growth-in addition to being tolerant of waterlogged and saline-alkaline soils, its vigorous nodulation and ability to fix nitrogen biologically (Ladha & Reddy, 1995; Chaudhury & Kennedy, 2004) [4, 19]-and that it will grow within the typical 45-60 day window between crops (most commonly between wheat and either transplanting rice or sowing rice) (Sharma *et al*., 1995; Tiwari *et al*., 1995; Kumar & Ladha, 2011; Verma *et al*., 2023) [7, 23, 27, 12].
Nighttime nitrogen is still a major factor limiting and costing you the most money in a cereal-based farming system with rice and wheat in the Indo-Gangetic Plains where farmers are using synthetic urea Nitrogen. Nitrogen Economies apply to all types of systems including non-biological nitrogen applications from nitrous oxides (NO), nitrate nitrate leachATION, and ammonia (Ladha *et al*., 2005; Dwivedi *et al*., 2016) [22, 20].

Therefore, nitrogen economies cover fields such as Nuse Efficiency, e.g., the amount of synthetically fixed nitrogen that can be replaced by biological nitrogen without affecting the yield of a crop and will provide a residual benefit for use by subsequent crops in the same field (Ladha *et al*., 2005) [22]. Major contributions of nitrogen created from green manure in sesbania aculeata through converting part of the carbon in the crop into carbon and biological sources of nitrogen directly contribute to reducing the need for synthetic nitrogen for use in the next crop while also improving the added carbon acceptance (the nitrogen supply characteristics of soil) of soil in the long term (Sharma *et al*., 1995; Sharma & Ghosh, 2000; Rahman *et al*., 2017; Khan *et al*., 2022) [7, 8, 9, 10].

The research conducted in the field provides a solid data set for various types of rice-wheat farming. This includes much of the extensive research done over many years throughout India, Pakistan, and Bangladesh along with some of the earlier studies done on deepwater rice farming, as well as flooding in rice production. These studies have quantified biomass production, nitrogen accumulation, and potential for fertilizer substitution associated with using Sesbania aculeata as a green manure plant under different soil types, management methods, and level of soil fertility (Sharma *et al*., 1995; Sharma & Ghosh, 2000; Rahman *et al*., 2017; Khan *et al*., 2022) [7, 8, 9, 10]. However, despite this strong body of scientific literature, most of the publications regarding Sesbania as a green manure are located primarily in older agricultural and plant-soil science journals, with only a limited number of INM studies in more recent years reexamining the role of Sesbania as a sustainable agricultural crop that promotes nitrogen-use efficiency and biological soil health. Therefore, an updated synthesis of the literature reviewed should be prepared to critically assess the current best available information about Sesbania (Choudhary *et al*., 2023; Verma *et al*., 2023) [11, 12].

To undertake this review will: (i) synthesize all current and historical evidence with respect to green manuring from Sesbania aculeata on biomass and nitrogen accumulation; (ii) provide a comparative assessment of the fertilizer-nitrogen substitution potential for nitrogen in Sesbania aculeata as well as the residual benefit of this green manure in rice-wheat, rice-rice, and maize-wheat cropping systems; (iii) consider factors (decomposition period, soil texture and salinity/alkalinity) that influence the effectiveness of Sesbania aculeata in various cropping systems; (iv) compare the performance of Sesbania aculeata with that of other green manures and grain-legume crop residues; and (v) identify methodological limitations, emergent long-term evidence, as well as unresolved research gaps. This review is reliant upon a historical and contemporary exploration of field and long-term experimental studies published on the effects of green manures from Sesbania aculeata between the 1980's and 2025 with a special emphasis placed on more recent (2015-2025) literature regarding integrated nutrient management.

## 2. Methodology of Literature Review

### 2.1 Literature Search Strategy, Inclusion, and Exclusion Criteria

A well-structured search was completed through many databases to find studies from peer-reviewed journals about Sesbania aculeata and its impact on nitrogen economy in cropping systems. Databases included: Scopus, Web of Science, ScienceDirect, SpringerLink (Plant and Soil, Nutrient Cycling in Agroecosystems, International Journal of Plant Production), PubMed Central, and regional agronomy journals (Indian Journal of Agricultural Sciences, Oryza, and Tropical Agriculture) plus AICRP-IFS and ICAR institutional reports. Main keywords were combined by using boolean logic and were: "Sesbania aculeata", "dhaincha", "jantar", "green manuring", "nitrogen economy", "substituting for nitrogen", "biological nitrogen fixation" and "rice-wheat cropping system". Because this phenomenon has been studied for many years, the time period covered was very broad (1985–June 2026), but 2015-2026 was highlighted for its timeliness; landmark trials that supported this topic's establishment were also included. Publications that include quantitative data on biomass, nitrogen or yield were included; however, peer-reviewed articles, duplicate records and data without extraction were not included. The search strategies and inclusion/exclusion criteria are shown in Table 1. The search criteria were two-part screening: (1) Titles and Abstracts and (2) Full Text. As a result of the two-part screening, we ultimately retrieved 32 studies from an initial search of roughly 700 records using PRISMA-based criteria shown in Figure 1.

**Table 1:** Literature Search Strategy and Inclusion/Exclusion Criteria

| Element | Details |
|---|---|
| Databases searched | Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed Central, regional agronomy journals |
| Search keywords | Sesbania aculeata; dhaincha; jantar; green manuring; nitrogen economy; nitrogen substitution; biological nitrogen fixation; rice-wheat cropping system |
| Search period | 1985 – June 2026 (broad, given long research history); emphasis on 2015–2026 |
| Inclusion criteria | Peer-reviewed, English-language studies on Sesbania aculeata green manuring with quantitative biomass/N/yield data |
| Exclusion criteria | Non-peer-reviewed sources; duplicate records; studies lacking extractable quantitative outcomes |
| Initial records identified | approx. 700 |
| Records after screening and selection | 32 |

The PRISMA-style approach was used to follow the selection criteria. Searches yielded about 700 records (n=700). After duplicates were removed (n=120), there were 580 records for title/abstract screening. Of these records, 410 were excluded for being irrelevant to Sesbania aculeata nitrogen-economy outcomes. After title/abstract screening, 170 records were full-text assessed and 138 were excluded due to no extractable quantitative data, being non-peer reviewed or being duplicate datasets across multiple publications of the same trial. The final qualitative synthesis included 32 studies. The process is depicted in figure 1.

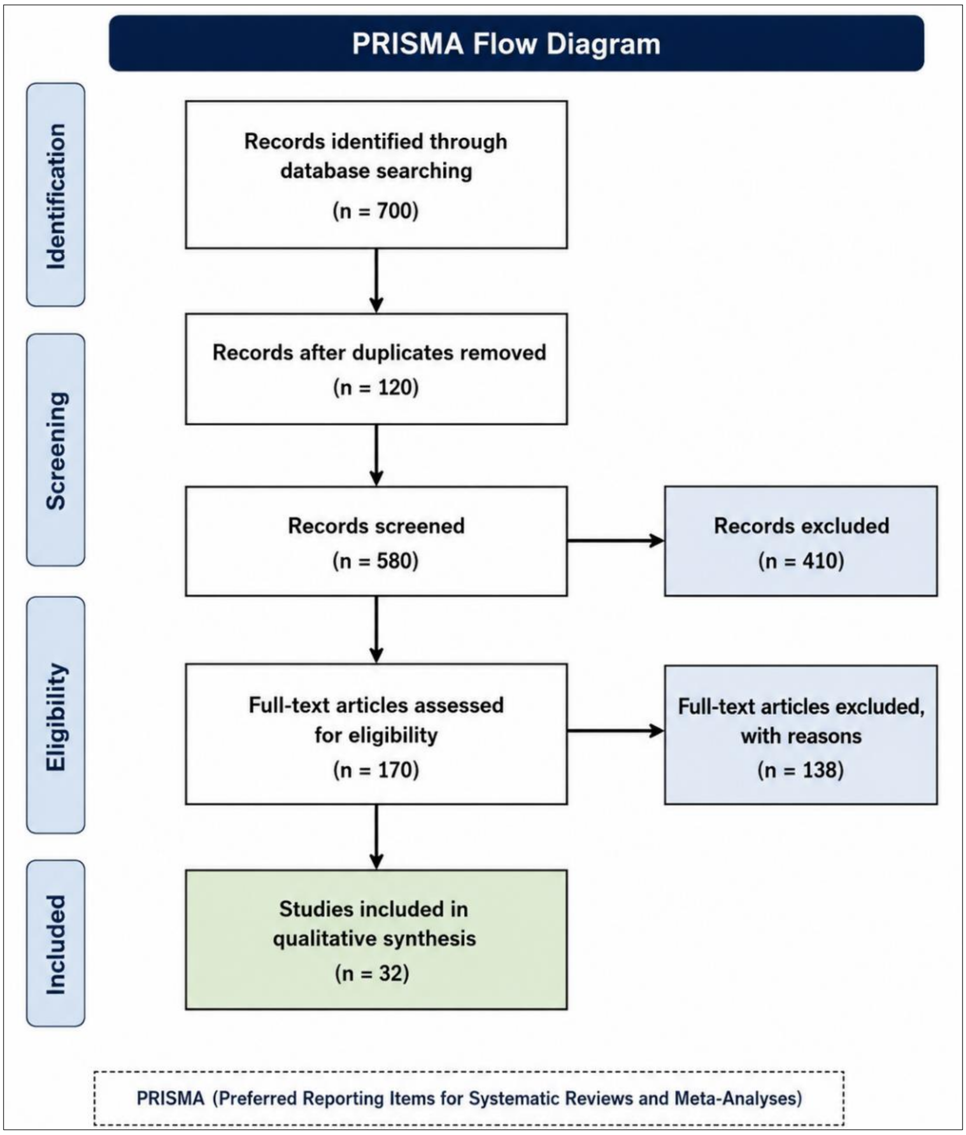


**Fig 1:** PRISMA flow diagram illustrating identification, screening, eligibility assessment, and final inclusion of studies (records identified n=700; duplicates removed n=120; screened n=580; excluded n=410; full-text assessed n=170; excluded n=138; included n=32).

### 3. Literature Review and Thematic Analysis

There are four main themes in the body of literature examined: (i) biomass and biological nitrogen fixation via Sesbania aculeata, (ii) fertilizer-nitrogen substitution and yield response in the first succeeding crop, (iii) residual nitrogen benefit to later crops and long-term integrated nutrient management, and iv) comparative performance to other green manures and grain-legume residues while factoring in the influence of soil type and residue decomposition management. Each theme will be discussed below with reference to studies providing a comparative analysis on each theme.

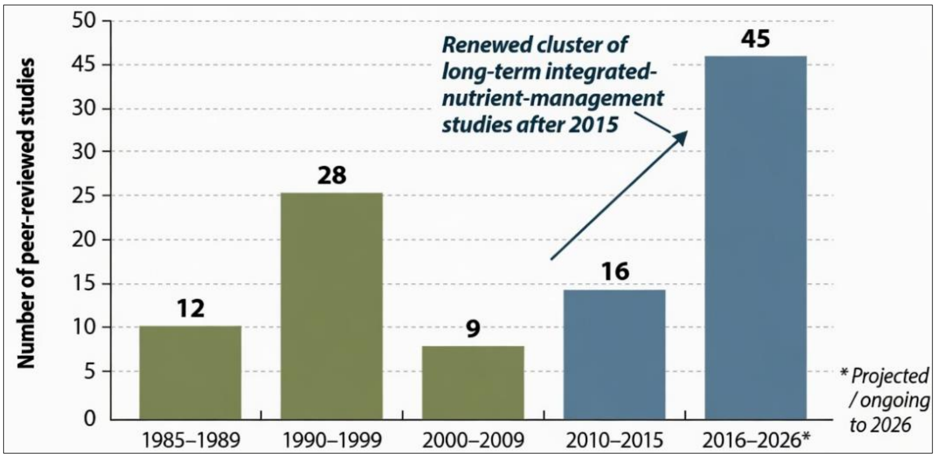


**Fig 2:** Publication trend (1985–2026) showing the number of peer-reviewed Sesbania aculeata nitrogen-economy studies by period, indicating a foundational research cluster in the late 1980s–1990s and a renewed cluster of long-term integrated-nutrient-management studies after 2015.

### 3.1. Biomass Production and Biological Nitrogen Fixation

Experiments have shown that Sesbania aculeata can produce large amounts of biomass and nitrogen in a short time. At Punjab Agricultural University, Ludhiana, a long term field trial discovered that as Sesbania grew from 30 to 60 days, it gained approximately 112 kg $ha^{-1}$ of nitrogen; biological nitrogen fixation was 77% to 82% for pearl millet and maize. Similarly, another 4-year trial with wetland rice showed that after growing 60 days, Sesbania developed 23 t $ha^{-1}$ of green matter, 4.6 t $ha^{-1}$ of dry matter and accumulated about 104 kg $ha^{-1}$ of nitrogen. The most recent agronomic/economic evaluation identifying maximum production from Sesbania, produced 4.75 t $ha^{-1}$ dry weight and 131 kg N $ha^{-1}$; greater than cowpea and greengram (Beri *et al*., 1989; Beri *et al*., 1995; Yadav *et al*., 2009) [13, 14, 15].

The data provided spans almost 40 years (in independent trials) across many locations (with differing soil types) and provides us with a very strong quantitative range: for Sesbania aculeata grown over a period of 45–60 days, average dry biomass production will be 4.6–6.0 t ha-1 and nitrogen (N) accumulation will be approximately 100–131 kg N ha-1. Biological fixation of atmospheric nitrogen (BNF) represents 77-82% (at least) of total accumulation; i.e., the majority of N in the biomass comes from BNF rather than uptake of N from the soil [13–15]. The fact that studies conducted since then (over several decades) and elsewhere (geographically) return similar results gives additional credibility of the value and potential for Sesbania as an effective agricultural metric for biomass and BNF production regardless of the small range in values due to varied times of growth, soil fertility levels, and conditions specific to the study being conducted (Beri *et al*., 1989; Beri *et al*., 1995; Yadav *et al*., 2009) [13, 14, 15].

### 3.2. Fertilizer-Nitrogen Substitution and Immediate Crop Response

The most thoroughly documented result of Sesbania green manure as a substitute for synthetic fertilizer nitrogen on subsequent crops, almost always rice, is the degree of nitrogen substitution and the amounts of nitrogen for 1:1 substitution have been found to be both quite large and relatively consistent across studies. For example, in one wetland/rice trial on alkaline soils, 24.7 tons/ha of Sesbania aculeata green manure (116 kg/ha of N after 45 days of green manure decomposition) produced a grain yield and N uptake equivalent to 122 kg of chemical N/ha applied to the rice crop, provided, however, that the green manure was allowed to decompose for at least 5 days following incorporation and prior to transplanting (Swarup, 1988) [16]. In another 4-year wetland/rice study, rice transplanted to the field one day after green manure incorporation (no fertilizer N added) yielded the equivalent of 120 kg of N/ha applied as urea. Also, when rice was incorporated into the field one day before transplanting (i.e., one day after incorporation) it yielded significantly more than with green manure incorporated 7 or 14 days before planting, and that approximately 40% of the carbon and 80% of the nitrogen was mineralized within the first 10 days after incorporation (Mahapatra *et al*., 1988) [17].

A study on the rice-wheat system was published by Plant and Soil. In that study, it was shown that using Sesbania as a green manure can replace the use of urea-N as a fertilizer. Specifically, 43 kg urea-N ha-1 were replaced for the direct application of urea to rice. In addition, there was a residual benefit to the next crop in that the residual effect of the Sesbania in the next crop of spring wheat was equivalent to 89 kg urea-N ha-1. Notably, the residual effect of the green manure was greater than the direct replacement for urea in the production of rice (Sharma *et al*., 1995) [7]. An example of using Sesbania in Bangladesh's lowland rice cropping systems demonstrated that even at 45 days of age, the Sesbania could provide 90 kg ha-1 of urea-N under light-textured soils with limited rainfall (Rahman *et al*., 2017) [9]. A four-year on-farm evaluation in Punjab, Pakistan has also shown that the use of green manures plus one-half of the recommended fertilizer will outproduce both rice and wheat.

In addition, it was noted that the total nitrogen levels in the soil increased with the addition of Sesbania (Khan *et al*., 2022) [10].

**Table 2:** Summary and Comparative Analysis of Selected Studies on Sesbania aculeata Green Manuring

| Author(s) & Year | System / Location | Key Biomass/N Data | N-Substitution / Yield Outcome | Limitations |
|---|---|---|---|---|
| Beri, Meelu & Khind [13] | Ludhiana, Punjab, India (long-term) | 50-d Sesbania: 112 kg N $ha^{-1}$; BNF 77–82% | N input basis for subsequent substitution studies | Reference-crop BNF method has inherent estimation error |
| Beri *et al*. [14] | Wetland rice, India (4-yr) | 60-d: 23 t green/4.6 t dry matter; 104–112 kg N $ha^{-1}$ | Rice yield at 1 DBT = 120 kg N $ha^{-1}$ urea-equivalent | Single soil type; decomposition-period focus only |
| Sharma, Prasad & Singh, 1995 [7] | Rice-wheat, India | Sesbania GM vs. pre-rice fallow | Substituted 43 kg N $ha^{-1}$ in rice; residual 89 kg N $ha^{-1}$ in wheat | Single location; mungbean residue comparably effective |
| Alkaline-soil wetland rice study [16] | Alkaline soil, India | 45-d: 116 kg N $ha^{-1}$ (S. aculeata) | Yield/N-uptake equivalent to 122 kg N $ha^{-1}$ chemical N | No residual soil-N effect detected post-harvest |
| Bangladesh BRRI studies [9] | Rainfed lowland rice, Bangladesh | 45-d Sesbania in light-textured soil | Complete substitution of 90 kg N $ha^{-1}$; ~70 kg N $ha^{-1}$ $yr^{-1}$ saved long-term | Cowpea outperformed dhaincha in mineral composition |
| Punjab, Pakistan on-farm trial [10] | Rice-wheat, Punjab, Pakistan (5-yr) | Sesbania broadcast in standing wheat | Half fertilizer + GM outyielded full fertilizer alone | On-farm variability; alkaline soil specific |
| Sharma & Ghosh, 2000 [8] | Flood-prone lowland rice, India | Intercropped vs. pure-stand incorporation | GM improved direct-seeded rice performance under flooding | Specific to flood-prone deepwater ecosystem |
| Yadav *et al*., 2009 [15] | Maize-wheat, India | Sesbania: 4.75 t $ha^{-1}$ DM; 131 kg N $ha^{-1}$ (highest among options) | N saving 57–67 kg $ha^{-1}$ in maize; 27 kg $ha^{-1}$ residual in wheat | Adoption low on farmer fields per authors' own note |
| 15-yr INM study, PMC 2023 [11] | Rice-wheat, India (15-yr) | GM as one of 5 INM components (50% substitution) | GM significantly increased NUE vs. 100% chemical fertilizer | Confounded with legume residue and FYM treatments |
| 8-yr INM study, IJPP 2023 [12] | Rice-wheat, India (8-yr) | CIF + GM vs. CIF + FYM vs. CIF alone | GM maintained yield comparably to FYM-amended CIF | FYM treatment showed larger yield gain than GM in this trial |

### 3.3. Residual Nitrogen Benefit and Long-Term Integrated Nutrient Management

According to studies, the use of rice as an alternative crop provides both a short-term effect (direct substitution) and a longer-lasting effect (through residual nitrogen contribution) (Sharma *et al*., 1995; Verma *et al*., 2023) [7, 12]. These studies have shown that there are higher amounts of residual nitrogen from rice than from wheat after the crop rotations are completed, which means more nitrogen is available for future crops. For example, the study on rice-wheat rotations found that the amount of nitrogen available from residual wheat after rice was greater than the amount of nitrogen that would have been available from rice yalnızca (89 kg N/ha vs 43 kg N/ha) (Sharma *et al*., 1995) [7]. It also noted that the large amount of nitrogen in any given rotation system can be slowly released, with residual nitrogen being released from two different sources: (1) from the previous crop and (2) from the planting of cover crops to improve soil structure and nutrient contents (Sharma *et al*., 1995) [7].

Based on the findings of the maize-wheat system study, residual nitrogen following Sesbania was found to be similar to the amount of residual nitrogen from both cowpea and greengram (27 kg N/ha vs 18-23 kg N/ha, respectively); however, this resulted in a greater amount of nitrogen savings for the current growing season in maize (57-67 kg N/ha) than for any of the prior seasons (Yadav *et al*., 2009) [15].

The long-term integrated nutrient management (INM) trials are what provide us with the best evidence of how Sesbania can contribute to the nitrogen economy of rice and wheat over time (Verma *et al*., 2023; Choudhary *et al*., 2023) [12, 11]. One set of trials over 15 years comparing the traditional use of 100% nitrogen to five different ways to replace about half of the nitrogen with the use of Sesbania acetylate through green manuring, legume residues integrated back into farming, using farmyard manure or retaining partial wheat/rice stubble showed that all five of these INM techniques were much more efficient in nitrogen use and performed better in terms of producing more nitrogen through mineralization and improving the biological activity of the soil than the 100% chemical fertilization (highly advantageous) method (Verma *et al*., 2023) [12]. The second INM trial followed for 8 years, directly compared conventional inorganic fertilizer (CIF) only vs. conventional inorganic fertilizer plus either farmyard manure (in terms of yield increased by 18.1% for rice) and using Sesbania green manuring techniques, showed that while farmyard manure produced the largest yield increase, green manuring with Sesbania produced similar effects on sustained productivity and soil health, thus confirming the conclusions of all of these previous longer-term INM trials (as discussed in Section 3.2) as well as much shorter-term substitution studies in the discussion above, that the nitrogen and economic benefit of Sesbania does not just exist temporarily as an artifact, but rather will continue to provide nitrogen and economic benefits to producers over time through the ongoing application of these techniques on a repeated annual basis.

### 3.4 Comparative Performance and Moderating Factors

The benefits of nitrogen economy associated with Sesbania aculeata are widely recognized; however, researchers also clearly identified that the performance of Sesbania aculeata relative to other competitive green manures or legumes is affected by the type of soil, the management of the decomposition process, and the types of legume alternatives available (Rahman *et al*., 2017; Choudhary *et al*., 2023) [9, 11]. For example, a comparison of cowpea to dhaincha in Bangladesh's rainfed lowland systems has shown that the mineral profiles and effects on rice yields of cowpea were superior to those of dhaincha, although dhaincha was still an effective and popular option as a green manure (Rahman *et al*., 2017) [9]. Within the Sesbania genus, S. rostrata has been identified many times as being superior to S. aculeata in biomass production, nodulation (including stem nodulation, where the nodules give rise to increased levels of nitrogenase activity), and total nitrogen accumulation. S. rostrata has been documented to completely replace urea-N in rice production if environmental conditions are favorable (Rinaudo *et al*., 1991; Chaudhury & Kennedy, 2004) [18, 19].

Soil type is an important moderating mechanism. A study about calcareous soil, which examined the use of Sesbania aculeata as a green manuring crop in combination with nitrogen fertilization when establishing transplant rice, found that while green manuring was still beneficial, the overall effectiveness of green manuring in calcareous soil was limited compared to that of the more favorable alluvial and alkaline soils where most substitutive (foundational) studies of green manuring were done (Rahman *et al*., 2018) [3]. It appears that calcareous soil chemistry may in fact interfere to some degree with both nitrogen mineralization and nitrogen uptake efficiencies when we consider green manure grown as part of an incorporated green manure system. A second consistent moderator is how soon the crop is incorporated; across several wetland-rice studies, incorporating a green manuring crop—like Sesbania—just prior to transplants (1 DBT) demonstrated higher overall performance compared to longer pre-incorporation periods (7 or 14 DBT), due to the fast (about 40% of C, 80% of N within 10 days) mineralization of the Sesbania biomass and the importance of synchronizing the release of N in time with the demands of the crop after transplanting (Beri *et al*., 1995; Mahapatra *et al*., 1988) [14, 17]. A synthesis of past studies estimated that, in multiple long-term trials throughout India and AICRP-IFS, on average, green manure can replace up to 50% of the nitrogen fertilization needs in different cropping systems while not losing any yield at all; in fact, partial factor productivity of N (PFPN) increased by about 50% during 1 kharif cropping season, as well as 25% in successive 2-summer cropping seasons, with green manure replacement (Dwivedi *et al*., 2016) [20].

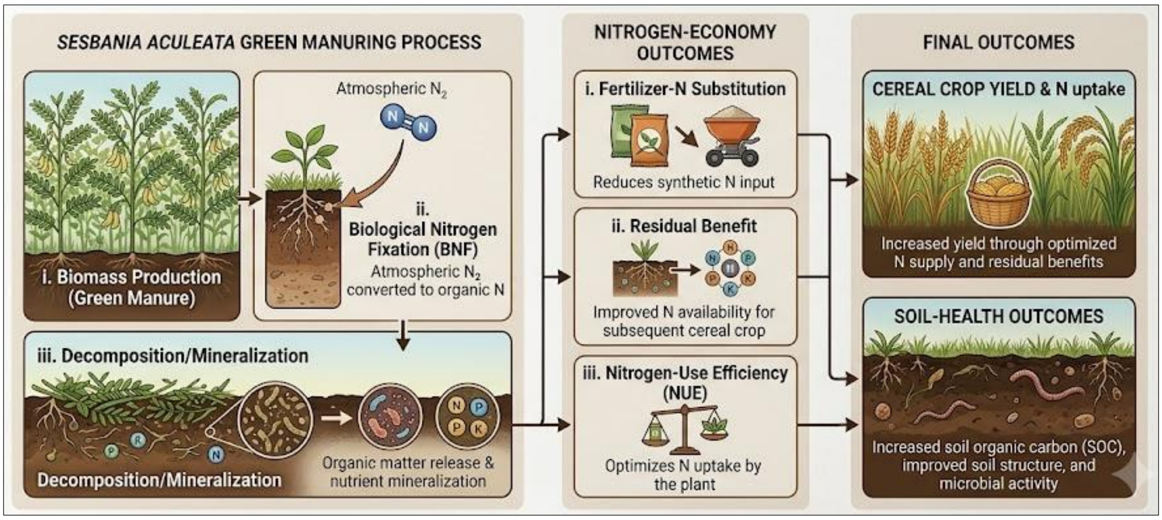


**Fig 3:** Conceptual framework linking Sesbania aculeata green manuring (biomass production, biological nitrogen fixation, decomposition/mineralization) to nitrogen-economy outcomes (fertilizer-N substitution, residual benefit, nitrogen-use efficiency) and final yield/soil-health outcomes in cereal-based cropping systems.

## 4. Research Gaps and Emerging Trends

### 4.1. Unresolved Issues and Knowledge Gaps

There are many gaps in the literature concerning these issues. First, BNF estimates are primarily made using a reference crop method, which can lead to inconsistencies in estimations. While there are some studies using isotopic methods to estimate BNF of Sesbania and other legumes, they are less common than reference crop methods (Boddey *et al*., 2000) [21]. Second, most data on substitution and residual benefit come from a limited number of long term experimental stations located in Punjab India and Pakistan and little evidence has been generated from other regions such as calcareous or saline soils where moderating factors have been documented but not quantified (Rahman *et al*., 2018; Choudhary *et al*., 2023) [3, 11]. Third, although there are many agronomic data demonstrating the benefits of using Sesbania as a green manure, multiple studies indicate that farmer adoption of Sesbania is very low due to the economic opportunity cost associated with a non-profitable crop grown during a short fallow period; however, little rigorous economic or behavioural analysis has been conducted to date regarding this adoption gap (Dwivedi *et al*., 2016) [20].

Fourth, comparative trials have been conducted that directly compare Sesbania aculeata to sister legumes S. rostrata which are superior agronomically as well as grain legumes which have nationally accepted marketable yields (cowpea, greengram). These trials have not always been specifically designed to separate nitrogen use efficiency outcomes from the economic yield advantage of the comparative crop, thereby limiting their ability to clearly delineate "which green manure is best" (Yadav *et al*., 2009; Rinaudo *et al*., 1991; Rahman *et al*., 2017) [15, 18, 9].

Fifth, there are only a few INM experiments documenting the long-term (multi-decade) trends of nitrogen stored in the soil and provided through the use of Sesbania green manures with sustained, repeated use versus those derived from using one or a few seasons of Sesbania green manuring (Choudhary *et al*., 2023; Verma *et al*., 2023) [11, 12].

### 4.2. Emerging Technologies and Future Developments

New directions for the use of isotopic ($^{15}$N) tracing techniques to more accurately differentiate between nitrogen from biological fixation versus nitrogen from the soil in Sesbania biomass should be undertaken. Evidence from the literature shows that the current method of using reference crops as a baseline to estimate the amount of nitrogen present in the plant is not as accurate as it could be (Beri *et al*., 1989; Boddey *et al*., 2000) [13, 21]. Long-term integrated nutrient management studies conducted over both fifteen and eight years, as reviewed above, should form the basis for continued investigations, with the additional goal of long-term measuring of soil nitrogen stocks over many decades and cumulative biological and electrochemical changes in the soil resulting from multiple applications of green manure (Choudhary *et al*., 2023; Verma *et al*., 2023) [11, 12].

Another new direction should include systematic evaluation of the financial opportunity cost of using green manures to determine the extent to which farmers are unwilling to adopt green manure as a source of fertility (Yadav *et al*., 2009; Dwivedi *et al*., 2016) [15, 20]. This can be done through partial or whole-farm budgeting models that estimate the agronomic advantages of using green manures as a source of plant nutrients compared to cash crops that would have been grown during the fallow period (Yadav *et al*., 2009; Dwivedi *et al*., 2016) [15, 20].

Lastly, the consistent finding that S. rostrata outperforms S. aculeata in terms of biomass and BNF provides an opportunity to address the deficiencies in performance of S. aculeata through either a breeding programme or through improved agronomic management of S. aculeata, or the creation of region-specific recommendations for which species of Sesbania to grow based on local environmental conditions (Rinaudo *et al*., 1991; Chaudhury & Kennedy, 2004) [18, 19].

## 5. Discussion

The evidence derived from almost 40 years of research indicates that Sesbania aculeata has consistently been demonstrated to be an effective green manure source for enhancing the nitrogen cycle in gram-based farming systems in South Asia (Beri *et al*., 1989; Beri *et al*., 1995; Yadav *et al*., 2009) [13, 14, 15]. Accumulated independent data shows that dry matter production is similar across geographic and temporal distances (4.6–6 t ha$^{-1}$ of material produced and 100–131 kg of nitrogen accumulated from biological nitrogen fixation), provides strong support for using sesbania as a green manure in multiple different geographical settings. This level of consistency between independent studies is rarely seen in agronomic literature, thus providing an exceptionally strong support for the reliability and reproducibility of sesbania as a green manure source in a variety of growing environments, although there is variation among growers and soils with regard to total amount of greenhouse gases that green manure sources will offset (Beri *et al*., 1989; Yadav *et al*., 2009) [13, 15].

Key concepts in interpreting the data include differentiating between immediate seasonal (direct) and carry over (residual) nitrogen contributions. Evidence was found that the residual benefit of using wheat (89 kg of nitrogen per hectare) was greater than that of immediate seasonal substitution with rice (43 kg of nitrogen per hectare), which indicates that most studies currently available provide underestimates of the potential system level nitrogen efficiency gains associated with Sesbania when only evaluated in the immediate succeeding crop (Sharma *et al*., 1995) [7]. This pattern is also established in the maize-wheat system by the consistent but somewhat lower residual benefit of wheat (27 kg per hectare) (Yadav *et al*., 2009) [15]. Thus, in order to accurately evaluate the nitrogen gene efficiency of Sesbania and compare it to other potential alternative crops, all crops within the rotation should be considered and not just the immediately succeeding crop (Sharma *et al*., 1995; Yadav *et al*., 2009) [7, 15].

The second and equally important observation is that the level of effectiveness is significantly affected by the time of inoculation and the type of soil. These two factors alone contribute significantly to the observed variability in the various reported substitution values for green-manure (ranging from 43 to 122 N kg/ha) in the studies reviewed. The trend for incorporation at the time of planting to provide superior performance compared to an extended period before incorporation is a true indication of the actual rate of mineralization of the incorporated green-manure materials (40% of carbon and 80% of nitrogen will mineralise within 10 days) rather than a result of inconsistent outcomes from the experimental design (Beri *et al*., 1995; Mahapatra *et al*., 1988) [14, 17]. Observed lower performance of green-manure in calcareous soils compared to alluvial Punjab soils indicates that results from studies conducted in the alluvial soils of Punjab should not be assumed to be representative of other soil types unless they are verified in that local area (Rahman *et al*., 2018) [3]. The sensitivity of the effectiveness observed to soil type also corresponds with what has been reported in other literature regarding green-manures and conservation agriculture that the amount of benefit derived from the green-manure/extraneous product is generally similar in terms of magnitude (but rarely in direction), due to differences in local environments.

An important consideration arising from the information gained during this synthesis relates to how Sesbania aculeata compares to other green manure crops (often S. rostrata) and grain legumes with a traditional marketable economic yield. In many studies, including some that mentioned it only briefly, cowpea or greengram produced nitrogen contributions that were equal or nearly equal to Sesbania's nitrogen contributions while providing their own seed yields that offer potential additional economic advantages compared to the potential economic benefit of growing Sesbania to produce nitrogen as a green manure crop (Rahman *et al*., 2017; Yadav *et al*., 2009) [9, 15]. This creates a practical tension in the current literature on Sesbania aculeata. While from an agronomic perspective Sesbania aculeata has a strong nitrogen economy, the opportunity cost of using the fallow period to grow a non-marketable crop would be a disincentive for farmers to adopt the use of Sesbania, particularly in smallholder contexts while the nitrogen contributions of dual-purpose legumes for grain production may be only marginally lower or equal in magnitude (Yadav *et al*., 2009) [15].

This review provides theoretical support for understanding the nitrogen economy of green manure, consisting of two pathways: direct substitution within the current crop or by providing residual nitrogen to future crops. The pathways are both based on a crop's ability to biologically fix nitrogen and how well the biomass is handled to meet the nitrogen demand of the crop. In the long term, the evidence presented across many trials supports Sesbania green manure as one key part of a sustainable approach to nitrogen management with respect to rice/wheat and other cropping systems. However, when making recommendations, it is also important to consider the timing and suitability of decomposition, the appropriate soil type, and the costs for farmers of leaving land fallow.

## 6. Conclusion

In Table 4, the quantitative nitrogen economy data from this review have been collected into an ultimate reference for each production system examined. Data presented here include the total biomass, fixation, substitution and residual benefits of the Cereal Cropping System assessed.

A total of thirty-two studies published in peer-reviewed journals were synthesised by this review to evaluate how growing Sesbania aculeata for green manure would affect nitrogen usage in cereal cropping systems. This review evaluates papers from fundamental field experiments in the late 1980s through present long-term integrated nutrient management trials that demonstrate the creation of large biomass with excellent biological nitrogen fixation during pre-rice or summer fallow periods by Sesbania aculeata, which grows quickly and reaches an average of 4.6 – 6.0 t ha-1 of dry matter and biologically fixes 100 to 131 kg of N ha-1; therefore, using Sesbania aculeata for green manuring substitutes approximately 43 to 122 kg of urea-N ha-1 to future crops for the immediate crop after growing Sesbania aculeata as green manure and provides future crops in a crop rotation with residual N benefitting from 27 to 89 kg of urea-N ha-1. Long-term integrated nutrient management trials, confirm that the above listed benefits result in long-term productivity gains of sustained nitrogen using efficiencies from 8 to 15 years of repeated applications; however the effectiveness of Sesbania aculeata as a green manure is affected by: natural decomposition rates of Sesbania aculeata, soil types (specifically the significantly reduced effectiveness when grown in calcareous soils), as well as how alternative green manure crops performed compared to alternative grain legumes.

According to researchers, this review recommends the use of isotopic methods of nitrogen-15, which provide more accurate estimates of biological nitrogen fixation, and extending the evidence available from alluvial soils of the Punjab region to other soil types like calcareous, saline, and lateritic, to assess the contribution of Sesbania to nitrogen economy over a full rotation of crops instead of one crop; and to complete a detailed analysis of the agro-economic barriers hindering the adoption of a fallow window.

For practitioners and policymakers, the findings of this review support the continued promotion of the use of Sesbania aculeata as a green manure. Extension workers should provide growers with extension recommendations that include best options for incorporation of Sesbania aculeata close to time of transplant (within one day prior to transplant, if possible) so as to synchronize the timing of nitrogen release with the nitrogen requirement of the subsequent crop; expectations associated with the effectiveness of Sesbania aculeata will depend upon the type of soil under production; and that alternative dual-purpose crops (i.e., grain legumes) should be considered when the opportunity costs of the fallow window restrict the little farmer from adopting.

Future research is encouraged to close the identified methodological, geographical, and economic gaps to better define and expand the practical use of Sesbania aculeata as a fundamental method for sustainable nitrogen management in high-intensity, cereal-based cropping systems.

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