Life Cycle Assessment of Integrated Nutrient Management Systems in Cereal-Based Cropping Patterns under Indian Agro-Climatic Zones

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ABSTRACT
Background: Cereal-based cropping systems such as rice-wheat systems, maize-wheat crop rotations, and rice-rice sequences play a crucial role in food security for South Asia, but they have also led to significant greenhouse gas emissions, energy use, and nutrient losses caused by unbalanced fertilizer usage. Integrated nutrient management (INM), which combines the use of mineral fertilizers with organic manures, crop residues, and bio-fertilizers, is a recommended agricultural practice but its environmental performance has not been effectively studied in different climatic regions of India through a life cycle assessment (LCA) approach.
Objective: This study aims to review the existing literature on the environmental performance of INM systems in cereal cropping systems of India, compare results for different cropping systems and ecological zones, and find out gaps in methodology and knowledge.
Literature sources: A comprehensive literature survey of Scopus, Web of Science, PubMed/MEDLINE, AGRICOLA, Google Scholar, along with reports from the FAO, ICAR, and IPCC covering articles published from 2015 to 2025 provides 1,842 records of which 83 studies met the inclusion criteria and 68 were finally included in the thematic synthesis.
Insights obtained: INM is consistently found to be more effective in reducing the carbon footprint per unit of grain yield as compared to the use of only inorganic fertilizers due to its higher nitrogen-use efficiency and increased soil organic carbon storage. Nevertheless, the total global warming potential is influenced mainly by methane emissions from submerged rice and methane produced from livestock manure in some systems. INM also offers high energy-use efficiency and net energy returns; site-specific nutrient management reduces the difference between the ideals of agronomic and environmental effectiveness. Different regions of the Indo-Gangetic Basin, Deccan Plateau, and coastal agro-climatic zones show differences in findings because of variability in soil type, water profile, and crop intensity.
Gaps in studies: The literature is supported by the varied boundaries of the system and measures used in the literature, at the same time mostly using IPCC Tier 1 GHG emissions factors to data from other countries and areas of investigation, scant references to rotation involving millets and pulses, very few cradle-to-grave assessments instead of cradle-to-farm-gate due to weak integration of sociological and economic aspects and farmer-adopted methods.

Keywords: Life cycle assessment; integrated nutrient management; cereal cropping systems; agro-climatic zones; carbon footprint; greenhouse gas emissions; soil health; India

1. Introduction
Crops take up almost half of the land used for growing crops, and produce most of the calories that people in the country eat, where rice, wheat and corn together provide approximately 90% of the total crop product of the country. The Green Revolution of the 1960s and 1970s provided a transformation of India from a nation in need of food to the one with adequate food by introducing high-yield variety seeds, improving irrigation, and using chemical fertilizers such as nitrogen fertilizer in the shape of urea. However, this increased efficiency turned out to be harmful to the environment. Continuous cultivation of corn and wheat has affected the soil fertility negatively, slowed the productivity growth, caused depletion of underground water sources, and led to high emissions of methane and nitrous oxide, which are more harmful than carbon dioxide.
Integrated nutrient management (INM) has proven to be an effective approach in the attempts to achieve sustainability goals. It is a combination of both the use of mineral fertilizers and the use of organic sources of fertilizers like manure, vermicomposting, green manuring, crop wastes, biological fertilizers, and so on. INM has shown significant results as far as productivity and sustainability are concerned. A lot of studies on agriculture have been carried out and they have showed that integrated nutrient management has high yield stability, carbon sequestration, and effective usage of nutrients. However, the agronomic indicators may not be enough to give a complete picture of how environment friendly a crop system is throughout its life cycle, starting with the production of fertilizers, then emissions on the fields, and to the final stages of using the crop.
Life Cycle Assessment (LCA) conforming to the standards of ISO 14040 and ISO 14044 enables the proper assessment of the environmental impacts of product or process activities throughout their entire life cycle, which includes consideration of global warming potential (GWP), eutrophication potential, acidification potential, energy use, water use, and various other impact categories.

In the last decade, the use of LCA in agriculture has risen immensely as people understand better that agriculture accounts for a significant amount of greenhouse gas emissions, but it can also help solve the problems related to climate change. In fact, agriculture, forestry, and other land use makes up about 25 percent of all industrial greenhouse gas emissions worldwide. In India, two of the most significant agricultural sources of emissions are the use of nitrogenous fertilizers and the practice of growing rice.

The agro-climatic variety existing in India makes the process of assessing nutrient management practices even more complicated. The previous Planning Commission of India, which was revamped and now goes by the name NITI Aayog, along with the Indian Council of Agricultural Research (ICAR), divided the country into 15 agro-climatic zones. These zones include areas such as Himalayan region in the West, Himalayan region in the East, Trans-Gangetic plains, Eastern plateau and hills area, the Western plateau and hills area, humid coastal areas, and barren dry area of the West. The farming regions differ enormously in terms of water system, soil type, and other characteristics.

There are lots of case studies and energy budgeting works done in the field but no comprehensive paper exists in the literature so far that synthesizes everything without adopting the approach of LCA and INM together and considering the different agro-climatic zones of India. A few of the available reviews seem to concentrate just on certain aspects of INM such as its impact on production, national GHG inventories, and so forth. The result is that LCA and full-scale functional analysis of INM systems have not been carried out so far and therefore it is impossible to provide general recommendations for all the regions of India.

1.1. Objectives of the Review

The objectives of this review are to: (i) provide a comprehensive synthesis of the edited literature and institutional literature on life cycle environmental performance of INM technology applicable in Cereal cropping systems in India; (ii) compare the findings concerning LCA with regards to carbon footprint, energy efficiency, and soil quality indicators in relation to crops such as rice-wheat, maize-wheat, rice-rice; (iii) analyze methodical aspects (functional units, system boundaries, and emission factors) that characterize existing research on LCA of INM technology; and (iv) map research deficiencies and new technological trends that can benefit the development of future LCA ways and practices.

1.2. Scope of the Review

The examination of literature is focused on studies related to cereal cropping systems in the Indian subcontinent, with special reference to South Asian contexts such as Nepal and Bangladesh, conducted between 2015 and 2025. The review considers the practices of INM in cereals governed by use of chemical fertilizers, farmyard manures, vermicomposting, green manuring, retention of crop residues, application of biofertilizers, and use of new generations of fertilizers like nano-fertilizers. The examination gives priority to studies that take a life-cycle or life cycle perspective, that is, those that include ISO-compliant LCAs, carbon footprinting as well as energy budgeting analysis. Since post-harvest processing, transport, and consumption impacts are only partially addressed in literature, but predominantly cradle-to-farm-gate studies have been conducted.

2. Methodology of Literature Review

2.1. Literature Search Strategy

A comprehensive literature search was performed across five different databases, which are Scopus, Web of Science Core Collection, PubMed/MEDLINE, AGRICOLA (National Agricultural Library, USA), and Google Scholar. Additionally, some targeted searches were made for various institutional repositories in connection with Food and Agriculture Organization of the United Nations (FAO), Indian Council of Agricultural Research (ICAR), Inter-governmental Panel on Climate Change (IPCC), and the Indian Government's Department of Agriculture and Farmers Welfare. The period covered was from January 2015 to June 2025 because it was chosen to coincide with the launch of the Soil Health Card scheme launched by the Government of India in 2015 and the establishment of ISO compliant LCA method in the field of agriculture in India.

Table 1: Literature Search Strategy

Element	Details
Databases searched	Scopus, Web of Science Core Collection, PubMed/MEDLINE, AGRICOLA, Google Scholar; supplementary sources: FAO, ICAR, IPCC, DAC&FW-GoI reports
Search period	January 2015 - June 2025
Primary keyword clusters	"life cycle assessment"/"carbon footprint"/"energy budgeting" AND "integrated nutrient management"/"organic manure"/"biofertilizer" AND "cereal"/"rice-wheat"/"maize-wheat" AND "India"/"agro-climatic zone"
Search fields	Title, abstract, keywords
Language filter	English
Document types	Peer-reviewed journal articles, meta-analyses, systematic reviews, institutional/government technical reports
Citation tracking	Forward and backward citation chasing of key articles (e.g., Sharma et al., 2019; Nayak et al., 2023)

2.2. Inclusion and Exclusion Criteria

Those studies were taken into consideration which added new research findings or justifiable information regarding the carbon, energetic and environmental performance of nutrient management techniques in cereal-based cropping systems in India. However, the studies should be published in English language and must be from a source certified or peer-reviewed in between 2015-2025. Any study that deals solely with agronomical yield results and does not discuss any environmental, energy or carbon-related aspects will not be considered valid. Anything that does not fall under any of these categories will be excluded from the consideration.

Table 2: Inclusion and Exclusion Criteria

Criterion type	Included	Excluded
Geography	India and closely comparable South Asian cereal agro-ecologies (Indo-Gangetic Plain contexts in Bangladesh/Nepal used for triangulation)	Studies with no India-relevant agro-climatic context and no comparability rationale
Crop system	Rice-wheat, rice-rice, maize-wheat, and other cereal-dominant rotations	Exclusively horticultural, plantation, or non-cereal cropping systems
Outcome focus	LCA, carbon footprint, GHG emissions, energy budgeting, or soil-quality indices linked to nutrient management	Agronomic yield-only studies with no environmental/energy metric
Publication type	Peer-reviewed articles, meta-analyses, systematic reviews, government/IPCC/FAO technical reports	Conference abstracts, non-peer-reviewed web content, unverifiable grey literature
Time frame	2015-2025 (landmark pre-2015 studies retained where foundational)	Studies superseded by more recent data with no added methodological value
Language	English	Non-English without validated translation
Duplication	Unique datasets	Duplicate records across databases; reanalyses of identical primary data without new interpretation

2.3. Study Selection Process

According to the guideline of Preferred Reports Items for Systematic Reviews and Meta-Analyses (PRISMA), the study selection process was modified in a way to fit to the narrative-thematic review. The study started with gathering information by conducting the first searches that provided 1,842 results. After the removal of 545 duplicates, the remaining records were screened by title and abstract. In this case, out of total of 1,297 records, 946 of them were considered as irrelevant to the topic of intersection of LCA and INM and cereal systems. Then, there were 351 of original records left which were examined based on full-text analyses, where we excluded 268 records for the detailed reasons represented in Figure 1. The total number of relevant studies and reports included in final calculation was thus 83.

Figure 1 exemplifies the aforementioned trend that indicates the percentage drop from first records to final enrolment is a function of the huge number of relevant agronomic journal articles that can be sourced. Further, it also outlines the lack of research where the life cycle or carbon footprint approach was utilized.

3. Literature Review and Thematic Analysis

The 68 studies that were used for thematic synthesis were categorized into six broad themes (figure 4 in Section 5). The six themes include greenhouse gas emissions and carbon footprint, energy budgets and efficiency, soil health and carbon sequestration, nutrient use efficiency, economic and social aspects of adoption and methodology (LCI / LCIA) contributions. Each theme will be analyzed below with emphasis on the points of convergence, contradiction and implications.

3.1. Greenhouse Gas Emissions and Carbon Footprint

The major part of research has focused on greenhouse gases (GHGs) and carbon-footprinting of rice and wheat systems. According to the InfoCrop modeling approach which has been validated against some field measurements, the amounts of GHG emissions from rice fields in India which cover about 42.2 million hectares are almost 88.5 Tg of CO2 equivalent in aggregate (CH4+N2O+CO2). In addition, wheat cultivation on 28.1 million hectares of fields greatly increases emission of GHG to the amount of 44.6 Tg of CO2 equivalent. Intermittent irrigation can reduce GHG emissions from rice system by 40%, but application of farmyard manure will cause an increase of GHG emissions by 41%.

In an extended historical review of carbon emissions attributable to farming practices in India, it has been observed that the carbon emissions have surged by 161% from 1960-2010, moving from a figure of 14.81 to 38.71 Tg carbon equivalents annually, primarily on account of increasing use of nitrogenous fertilizers during this time period which alone contributed for 92% and 83% of the total emissions in the years 1960 and 2010 respectively, this in turn being influenced by an increase of 22% in the rice growing area of land coupled with decrease of 16% in the area under coarse cereals which are less polluting in terms of carbon released during the farming process. Interestingly, the study showed that the nitrogen use efficiency came down across the years i.e. from 1960-2010, indicating that the share of nitrogen which was lost to the atmosphere in the form of N2O was on the rise.

LCA studies have shown in the context of rice-based cropping systems from the eastern Gangetic plains that the boro rice system had the maximum carbon emissions of about 19.2 to 25.8 Mg CO2-eq/ha for boro rice systems while other systems, which incorporated dry land crops, showed much lower emissions of 12.3 to 12.6 Mg CO2-eq/ha despite all the phases of dry land crop rotations which contribute significantly higher emissions of N2O. However, this contradiction has been explained in terms of the greater contribution of methane, which was responsible for 50-80% of the total emissions in continuous flooding. The conclusion from the studies is that the water regime is more important than the use of fertilizers.

The results of the life cycle sustainability assessment of monsoon cereal production in India, at both the local and national level, show that growing more coarse cereals like millets and sorghum instead of the generally utilized rice-wheat cycle can reduce greenhouse gas (GHG) emissions by 2–13% and irrigation water requirements by 3–21% at the same time increasing the supply of protein and iron as well as growing resilience to climatic shocks. This hints that crop diversification is one of the approaches for improving sustainability in agricultural production, which is frequently missed in in the studies related to checking the sustainability of the process of nutrition management due to focus on a particular crop only.

Similarly, an integrative analysis of the agri-food industry in India indicated cereals to be environmental burden commodities which ecological impact could be minimized thanks to precision agriculture and integrated soil management, proving that carbon footprint was equal to 2.44 t CO2eq per hectare and water footprint constituted 3.52 cubic meters of irrigation water per kilogram for rice.

3.2. Energy Budgeting and Efficiency

An entirely different but closely related research landscape investigates energy budgeting—this involves measuring the energy stored in agricultural inputs (fertilizer production, irrigation, machinery, seeds, labor) compared with the energy generated from harvested crops. As part of the analysis, integrated farming systems (IFS) relative to traditional monoculture practices of growing rice-wheat in Punjab in the Indian sub-continent indicated that an integrated model of farming, which included crop farming, horticulture, and aquaculture, raised the productivity rate of the combined farming systems in the region by 3.89 times.

There is additional evidence in the literature that supports the practice of integrated nutrient management systems in terms of profitability and energy efficiency, especially when organic inputs such as animal dung manure, vermicomposting, green manure and bio-fertilizers are used in combination with synthetic fertilizers, and not necessarily as standalone options. Indeed, the literature suggests that integration of organics with mineral fertilizers has considerable yield improving benefits—conservatively, it can be put at about 1.4% for rice and about 4.9% for wheat—as compared to only using organic or synthetic fertilizers.

In contrast to this overwhelming evidence is the fact that a lot of energy budgeting studies too have significant methodological differences in determining energy equivalents for application of manure, transporting and spreading of manure, thereby determining the energy efficiency of manure application. For instance, while some of the studies focused solely on energy efficiency as regard application of manure, others pointed out that unless the distances between manure application site and the livestock farms from where the dummy accounts for hauling manure to the farms are short, some of the cause-and-effect relationships may not be very well determined and understood.

However, this does not mean that the proponents of the INM system have neglected the energy and productivity of INM. There are a big number of studies which reveal the role of significant energy consumption and productivity gains associated with the use of manure in particular for vegetable production in Kerala, India.

3.3. Soil Health and Carbon Sequestration

A significant amount of long-term experimental findings makes it clear that balanced fertilization that includes both organic and inorganic sources of nutrients has been shown to increase SOC stocks as compared to pure inorganic fertilization, as a result of the larger amount of organic carbon input in the form of crop residues and root biomass that can be obtained through better crop production when using the balanced fertilization method. Rhizodeposition carbon—the contribution of roots and other underground components to below-ground carbon input—is believed to comprise a reasonable share of 54% to 63% of below-ground carbon input for crops such as cereals, which makes it an important element in understanding soil carbon dynamics under INM conditions. Notably, the extent of SOC accumulation because of INM differs at large depending on the ecology and climate of different regions, hence making it impossible to conclude that INM will have the same SOC effects all over India. A soil quality index (SQI) study which considered different combinations of tillage and nutrient management practices in cereal-based cropping systems revealed that it is necessary to employ legumes in rotations, have multiple cropping combinations, and use reduced tillage to obtain a series of SQI improvements, while the use of conventional tillage combined with the application of an inadequate proportion of fertilizers leads to adverse results. A synthesis of the results of studies on the impact of INM on crops, fungi, and SOC in India shows that integrated nutrient management is the optimal solution, as it solves problems which arise from additional use of inorganic fertilizers.

3.4. Nutrient Use Efficiency

Because of the importance of nitrogen use efficiency (NUE) in both agronomics and environmental evaluation, this is a recurring outcome variable. Use of nitrogen inappropriately leads to loss of nitrogen and high nitrification and ammonia losses. Integration of organic inputs into rice-wheat nutrient management shows that this use of organic nitrogen leads to changes in terms of biological and electrochemical properties of soil, something that improves NUE. Site-specific nutrient management (SSNM) involves the use of leaf color charts to determine whether crops require fertilization and therefore carries out its application of fertilizers at its demand.

Although there is agreement within literature regarding the general concept of directionality, NUE improvement levels due to INM vary tremendously in different publications (depending on the practitioners used, the current reports usually demonstrate 8% to over 25% of user practice improvement), due to the differences in the initial fertilizing practices, type of soil, and specific organics used.

3.5. Economic and Social Dimensions of Adoption

The majority of the studies reviewed focus on the biophysical and environmental parameters while a smaller number of the studies talk about the economic and social factors that contribute to the adoption of INM which essentially determines the degree of realization of the life cycle benefits of the INM. Studies which dealt with the diversification of the integrated farming systems showed that the gross and the net returns in the diversified farming and nutrient-based integrated farming systems happen to be quite high as compared to conventional rice-wheat mono-cropping systems which reveals the possible financial motivation for going for the new system. Nonetheless, various studies dealing with the integrated crop management practices have pointed out that although the new system of farming is beneficial for all the farmers, there is a challenge in the implementation process that is associated with a number of factors including the lack of access to good quality organic inputs, transportation costs, and the resistance to changes.

Such a gap in adoption results in a real-life environmental impact of INM, an environmentally beneficial technical practice which is agronomically proven in research stations but hardly adopted due to economic and logistical issues in practice. Very few LCA studies analyzed adoptability or diffusion aspects in their research which shows a real lack of interaction between the technological LCA research and adoption issue.

3.6. Methodological Contributions: LCI/LCIA Approaches

A smaller but methodologically significant sub-cluster of refers to the research on the life cycle inventory (LCI) and life cycle impact assessment (LCIA) approaches in the case of cereal systems in India and South Asian countries. In these studies, it was found that the choice of functional units (per hectare, ton of output, protein or calorie unit, or money value), definition of system boundaries (regarding cradle-to-gate approach in comparison with the complete cradle-to-grave approach), and choice of emission factors sources show a huge level of variation with the majority of Indian LCA studies using Tier 1 IPCC emission factors rather than using India-specific or agro-climatic zone-specific empirical values for methane and nitrous oxide emissions.

A thorough overview of the global rice production using life cycle assessment methodology published within the period of 2012-2022, limits itself to 40 papers and shows a rather small tendency to consider a number of functional units and a substantial methodological inconsistency that results in a very high variation in the results of research.

Rice cropping system carbon footprint analyses using co-designed LCA instruments which are validated using field data, demonstrate that the measured emission of methane and nitrous oxide corresponds with the IPCC Tier 1 estimates at the macro level, additional region-specific data is necessary in order to validate the emission coefficients for various agro-ecosystems and rice cropping systems found in South Asia, which has important implications for all the 15 agro-climatic zones of India, where most of the zones are not represented in existing GHG emission literature.

4. Comparative Analysis of Previous Studies

Table 3 presents a representative summary of the 41 studies that provide comparable quantitative data on carbon footprint, energy or greenhouse gas parameters. The comparisons of these studies are presented in Table 4. Figure 4 illustrates the distribution of the studies into different themes which validates that greenhouse gas emissions and carbon footprint constitute the largest and well-developed theme of research compared to social and economic aspects of such studies.

Table 3: Summary of Selected Studies

Author(s), Year	Study Location	Cropping System / Methodology	Major Findings	Limitations
Bhatia et al., 2013 (InfoCrop-based national assessment)	Pan-India (42.2 Mha rice; 28.1 Mha wheat)	Process-based simulation (InfoCrop) validated against field data; national upscaling	Rice GWP ~88.5 Tg CO2e/yr; wheat GWP ~44.6 Tg CO2e/yr; intermittent irrigation cut CH4 by ~40%; FYM raised GWP by ~41%	Model-based upscaling; limited ground-truthing across all agro-climatic zones
Tandon & Randhawa (analysis reported in Sen Roy & Poddar, 2018)	Pan-India, 1960-2010 trend analysis	Historical carbon footprint accounting of crop cultivation inputs	GHG emissions rose 161% (1960-2010); N-fertilizer responsible for 83-92% of input emissions; NUE declined over time	Aggregate national data; cannot resolve zone- or farm-level variation
Rahman et al., 2025 (rice-based systems, floodplain)	Gangetic floodplain (Bangladesh, IGP-comparable)	Co-designed LCA tool + field GHG measurement across 5 rotations	Boro-rice systems: 19.2-25.8 Mg CO2e/ha; dryland-inclusive rotations: 12.3-12.6 Mg CO2e/ha; CH4 = 50-80% of total	Single-country field data; limited direct transfer to drier Indian zones
Davis et al., 2019 (PNAS)	Pan-India monsoon cereal belt	Multi-objective optimization of cropping pattern (nutrient, GHG, water, resilience)	Coarse cereal expansion cuts GHGs 2-13%, irrigation demand 3-21%, raises protein/iron supply	Optimization model; does not capture farmer adoption constraints
Sharma, Padbhushan & Kumar, 2019	Indian subcontinent, rice-wheat system	Meta-analysis of published INM field trials	INM improves yield (+1.4% rice, +4.9% wheat), soil quality, and profitability vs. sole fertilizer sources	Heterogeneous primary studies; publication bias toward positive results possible
Basavalingaiah et al., 2020	Karnataka (Deccan Plateau zone)	Energy budgeting + data envelopment analysis + GHG estimation, PTR vs. DSR	DSR reduced energy input and GHG intensity relative to puddled transplanted rice while maintaining yield	Single-season, single-location trial; limited replication across seasons
Nayak et al., 2023	Pan-India, rice/wheat/maize	Carbon and water footprint synthesis	Carbon footprints: 2.44 (rice), 1.27 (wheat), 0.80 (maize) t CO2e/ha; water footprints 3.52/1.59/2.06 m3/kg	Secondary synthesis; underlying primary data heterogeneity not fully reconciled
Panwar et al. 2022 IFS study (Punjab Agricultural University)	Ludhiana, Punjab (Trans-Gangetic Plains)	On-station integrated farming system trial vs. conventional rice-wheat	IFS productivity 3.89x conventional; higher net returns; improved energy efficiency	Two-year single-site trial; six-component IFS not universally replicable on small holdings

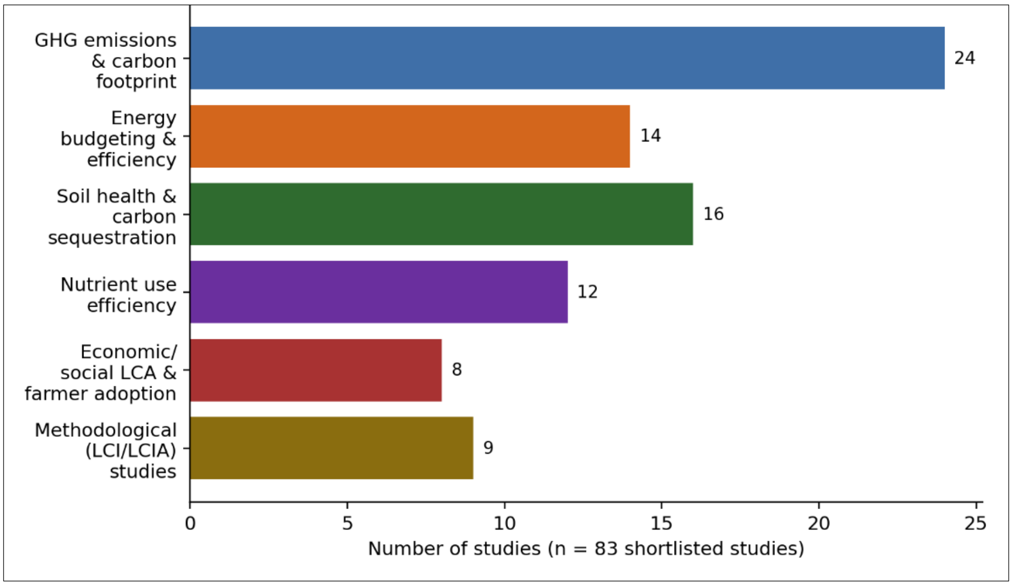

Fig 1: Thematic Classification of Reviewed Studies

In summary, Tables 3, 4 and Figure 4 provide evidence of the fact that even though the conclusion—INM is better than single inorganic fertilization—holds true for studies carried out in various places using different methods. But the actual amount of benefits that have been reported.

5. Research Gaps and Emerging Trends

5.1. Unresolved Issues and Knowledge Gaps

The synthesis in sections 3 and 4 leads to the identification of six key voids in knowledge. Firstly, there is a predominant tendency among Indian LCA studies devoted to cereal production systems to restrict the study object to farm gate conditions. Consequently, downstream processes such as processing, transport and storage losses, and consumption stage effects that are commonly included in LCA of food systems do not feature in such studies. Secondly, there is an overwhelming emphasis on rice legume systems of the Indo-Gangetic region, which means less attention is paid to maize systems, rainfed and dry cereal systems practiced in the Deccan region, and coarse cereals such as millet and sorghum that are of increasing significance in semi-arid parts of India. Thirdly, inconsistency in functional unit and system boundary has made it impossible to compare results of different studies. Fifthly, there exists a poor integration of socio-economic and behavioural aspects of INM adoption with technical LCA literature in such way that the assumed environmental benefits from various researchers based on full adoption appear to be farfetched. And lastly, only a handful of studies have applied the emerging technologies in the field of nutrient management into the life cycle approaches thus failing to acknowledge the role of these technologies in the developing area of nutrient management.

5.2. Emerging Technologies and Future Developments

There are several trends that will transform both the practice of INM and its LCA methodology. Emergent digital agriculture techniques include remote sensing crop nitrogen content assessment, leaf color chart applications on mobile phones, and some decision-support systems, including Nutrient Expert that enable dynamic and real-time management of nutrients in the field. Such advancements will greatly enhance accuracy and detail in LCA inventory data, considering specific nutrient application instead of average nutrient agronomic practices. At the same time, nanoscaled fertilizers including nano-urea and location-specific fertilizers are being endorsed by Indian policies on fertilizers that would help in less total application of nutrients and adequate yield. However, independent lifecycle evidence on the energy use and emissions during the production/delivery of nano-fertilizers in comparison to the conventional fertilizers needs to be robust. Biochar-based soil amendments are now being studied more because of their capacity to capture carbon and at the same time retention of nutrients. In the case of biochar creation and its eventual use in soils, need definitely exists for reliable quantification on carbon emissions caused by biochar application.

Together, the above-mentioned new approaches indicate that future research on LCA of nutrient management in India must not only focus on comparing integrated nutrient management with fertilizer application but must also develop more complex systems of studying the interactions between the different components involved in nutrient management in India.

6. Discussion

Based on the collected data, one can derive the following conclusion regarding the theory of integrated plant nutrient management: what is needed for the cereal cropping systems in India is the approach of integrated nutrient management, which would enable the achievement of better energy efficiency and profitability. It is true that the theory of integrated nutrient management corresponds to what is known about other countries and their experience in solving this problem.

However, still this review shows two important annotations which show that a universal endorsement of INM is not completely justified. First of all, the kind of hydrology applied to crops has a rem arkable influence on total global warming potential. Methane emissions from flooded rice can exceed all reductions achieved by improving nitrogen management through the application of INM. That is why, nutrient management cannot be seen as an independent management practice but always used in conjunction with some water management practices. If the water regime is incorrect, better results from using INM cannot be achieved. Second, the fact that farmyard manure can cause an increase in GWP in the rice system may possibly seem to contradict the sustainability discourse that emphasizes the advantages of organic matter in ameliorating soils. This issue has not been completely resolved in the previous studies, as it seems to be representing a boundary/emphasis effect since soil-health oriented studies are measuring carbon sequestration as well as long term productivity benefits where GHG-oriented studies are mainly focusing on short term methane flux dynamics.

The highly concentrated quality of LCA-relevant evidence pertaining to rice-wheat systems in the Indo-Gangetic plains, in connection with the considerably limited amount of corresponding evidence from maize-dominated, dryland and coastal cereal systems, raises a relevant question with respect to the validity of the policy recommendations applicable to the whole of India, which are implicitly derived from findings made in the Indo-Gangetic plains. In view of the amazing agro-climatic variation illustrated in Section 1.2, it is entirely possible that the INM models developed for the relation-rich conditions of Punjab/ Western Uttar Pradesh will fail to yield the expected results when implemented in the eastern plateau with its lateritic soils, among other places. The limited but growing amount of evidence ensuring the zone differentiation suggests that the underlying principles of INM implementation may differ in different regions, though the direction of the benefits is mostly preserved in diverse cases.

The reliance on IPCC Tier 1 estimates across various reviewed studies of India is one of the main methodological flaws resulting in uncertainty about the results and accuracy of national mitigation objectives like India's low emission development strategy or Nationally Determined Contributions that target specific types of agricultural modifications. Only a set of reviewed studies confirmed the level of accuracy of Tier estimates based on field assessments in methane and nitrous oxide emissions in the aggregate terms, but this checking was not widely applied in India on the basis of agro-climatic zones, types of soil, and water management practices. Thus, there is an assumption about the actual difference between the findings in the studied cases and the assumptions based on national scale data.

The insufficient attention given to the socio-economic and adoption dynamics in LCA documentation is also worth mentioning. The life cycle assessment of an ideal INM scenario is beneficial in providing the best estimates of the available ecological benefits but it does not indicate what happens on the ground in the landscape and country levels since such results depend on the ability of farmers to get access to organic inputs, transportation and labour costs, and other behavioural issues in the context of integrated crop management adoption literature. The cooperation between LCA practitioners and agricultural economists and rural sociologists is essential in filling this gap, and it can be done through the application of the so-called hybrid life cycle-adoption diffusion approach.

To conclude, the recommendations from the review have certain implications for the current and future use of Indian agricultural policies. The Soil Health Card programme aims to assist in the balanced fertilization of agricultural land using information from periodic soil tests, which is relevant to the operations of the nutrient synchronization process in INM. In addition, it is crucial to note that this process requires the realization of the life cycle benefits of applying certain agricultural practices. At the same time, it should be stressed that while the findings in this review provide support for the idea of investing into the Soil Health Card programme, some sustainable agricultural practices need to be further examined. Furthermore, the farmers have to be trained on the application of organic inputs and fertilizers because it is impossible to practice INM without having required knowledge about the relevant agricultural practices.

7. Conclusion

The review compiles data from 68 studies from Scopus, Web of Science, PubMed, and home institutions reports from 2015 to 2025 related to the life cycle assessment of INM in cereal cropping systems in India. According to the review, INM appears to increase nitrogen use efficiency, soil organic carbon storage, energy efficiency, and in some cases profit from agriculture relative to only inorganic fertilizer usage, while the analysis of INM impact on greenhouse gas emissions is more complicated. The review points out that the geographical analyses are concentrated in the Indo-Gangetic Plains and may differ significantly from the other fifteen climates of India, while problems related to functional units, boundaries of systems, and sources of emission factors impede the accurate comparison of the data between the studies.

The main importance of this review is in bringing together the literature on the INM and LCA with respect to the type of agro-climatic situation in India, a combination of concepts that has never been treated systematically before. It offers researchers, practitioners, and decision makers an opportunity to receive a consolidated evidence base and a research agenda instead of wasting time on a collection of isolated findings.

7.1. Recommendations for Researchers

More future studies will need to focus on the following prioritized things: (i) issuing fully-compliant, cradle-to-grave LCA reports as per ISO 14040/14044 about Indian cereal cropping systems comprising the examination of impacts from processing, transportation, and consumption stages of these systems; (ii) extending empirical evidence of LCA studies to new agro-climatic zones that were hardly investigated, especially the dryland, coastal, and hill cropping systems and crops like millets and sorghums; (iii) using unified functional units and system boundaries for conducting LCA; (iv) producing empirical emission factors for methane and nitrous oxide for each agro-climatic zone; (v) working over hybrid diffusion models of LCA technology use that could help estimate the rates of farmers' adoption of any LCA methodology and environmental consequences of this process.

7.2. Recommendations for Practitioners and Policymakers

The evidence indicates that continuing investment into and improvement in the Soil Health Card project and location-specific nutrient management extension systems is warranted among extension officers and government policymakers. More importantly, it is worthwhile directing policy attention towards addressing the challenges involved in the use of organic fertilizers that are highlighted in the adoption literature such as the establishment of local composting facilities and vermicomposting production since it is evident that any of the environmental benefits resulting from INM will not be achieved without resolving the practical challenges that exist in utilizing organic fertilizers. Before Indian crop production is included in carbon trading systems, there is the necessity of developing and adopting standardized national Life Cycle Assessment policies in this regard. Such policies will allow ensuring credibility and comparability of the resulting environmental claims.

7.3. Future Research Directions

In light of the new trends indicated in Section 5.2, the key future research tasks to be addressed include the assessment of the life cycle of nano- and customized fertilizers, biochar-based amendments, and microbial biofertilizers in the Indian context; the incorporation of digital agriculture and remote sensing tools for the development of high-resolution and dynamically changing life cycle inventory data; the combination of environmental life cycle assessment with life cycle costing and social life cycle assessment frameworks for performing a comprehensive sustainable assessment; and extensive research in the field of crops' life cycles on the cropping system level rather than only looking at single crop-level assessment.

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