International Journal of Plant & Soil Science

Volume 38, Issue 4, Page 345-360, 2026; Article no.IJPSS.153491
ISSN: 2320-7035

Nutrient Balance Sheet Approach for Sustainable Soil Fertility Management in the Bundelkhand Region: A Narrative Review

Saniya Syed [a], J K Tiwari [a], Deo Kumar [a*], Devendra Singh [a] and Krishnanand Yadav [a]

[a] *Department of Soil Science and Agricultural Chemistry, CoA, BUAT Banda, U.P. 210001, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i46052

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/153491

Review Article

Received: 03/02/2026
Accepted: 11/04/2026
Published: 17/04/2026

Abstract

The nutrient balance sheet approach provides precisely this kind of systematic accounting. By quantifying all significant pathways of nutrient addition and removal within a defined agricultural system—whether a farm, watershed, or district—the approach generates a net nutrient balance that indicates whether soil fertility reserves are being replenished, maintained, or depleted over time. The Bundelkhand region of north-central India, encompassing parts of Uttar Pradesh and Madhya Pradesh, is characterised by a semi-arid climate, drought-prone conditions, and widespread soil degradation that severely constrains agricultural productivity. Persistent nutrient mining, imbalanced fertiliser application, and the erosion of fragile soils have progressively depleted the fertility capital of this ecologically sensitive landscape. The nutrient balance sheet approach—a systematic accounting of nutrient inputs and outputs within an agricultural system—offers a

**Corresponding author: E-mail: kumar.soil@rediffmail.com;*

Cite as: *Syed, S., Tiwari, J. K., Kumar, D., Singh, D., & Yadav, K. (2026). Nutrient Balance Sheet Approach for Sustainable Soil Fertility Management in the Bundelkhand Region: A Narrative Review. International Journal of Plant & Soil Science, 38(4), 345–360. https://doi.org/10.9734/ijpss/2026/v38i46052*

rigorous and spatially relevant framework for diagnosing soil fertility decline, guiding fertiliser recommendations, and informing sustainable land management policies. This narrative review synthesises existing knowledge on the agro-ecological context of Bundelkhand, the theoretical underpinnings of the nutrient balance sheet methodology, and its practical implications for improving soil fertility management in the region. The review identifies that Bundelkhand soils are predominantly deficient in nitrogen, phosphorus, sulphur, zinc, and boron, whilst potassium status varies considerably across soil types. Negative nutrient balances for most major nutrients reflect chronic over-extraction and under-replenishment of soil fertility reserves. Integrated nutrient management strategies combining mineral fertilisers, organic amendments, biofertilisers, and green manures are discussed in the context of restoring nutrient equilibrium. The review further addresses the roles of climate variability, water erosion, and policy frameworks in shaping nutrient dynamics. It is concluded that the institutionalisation of periodic nutrient balance assessments, calibrated to the specific soil–crop systems of Bundelkhand, is essential for achieving long-term agricultural sustainability, food security, and environmental resilience in the region.

Keywords: Nutrient balance sheet; soil fertility; Bundelkhand; integrated nutrient management; dryland agriculture; nitrogen; phosphorus; potassium; soil degradation; sustainable agriculture.

1. Introduction

Modern agriculture heavily relies on chemical-based fertilizers. The excessive use and inefficient distribution of crop fertilizer nutrients lead to significant changes in soil properties. Long-term fertility experiments give the ideal platform for understanding the alterations in soil properties, productivity, nutrient imbalances, deficiencies, and overall impact on soil health and quality. As the demand for food and fiber grows in the Indian subcontinent, researchers and planners have focused on intensifying agriculture through the use of modern techniques such as high-yielding irrigation, plant protection measures, varieties, and high-analysis fertilizers (Khambalkar et al., 2025; Malo & Saha, 2025). Food security in the twenty-first century is fundamentally a soil security challenge. Globally, agricultural systems are under mounting pressure to sustain and enhance crop production on a finite and increasingly degraded land resource base. Central to this challenge is the management of soil fertility—the capacity of soil to supply nutrients in adequate quantities to sustain crop growth and maintain the biological, chemical, and physical properties essential to long-term productivity. The progressive loss of soil fertility through nutrient mining, erosion, acidification, and organic matter depletion has been identified as a primary driver of yield stagnation and rural food insecurity across many developing countries (Lal, 2009). Addressing this crisis requires not merely the application of fertilisers, but a systematic understanding of how nutrients flow into, through, and out of agricultural ecosystems.

Soil nutrient monitoring plays a vital role in advancing sustainable agriculture by maintaining soil health, optimizing crop productivity, and minimizing environmental impacts. Soil nutrients are fundamental in regulating ecosystem structure and function, as they influence critical processes such as water retention, carbon storage, soil stability, crop health, and the maintenance of biodiversity and ecological resilience (Sobhy & Anandhi, 2025). The nutrient balance sheet approach provides precisely this kind of systematic accounting. By quantifying all significant pathways of nutrient addition and removal within a defined agricultural system—whether a farm, watershed, or district—the approach generates a net nutrient balance that indicates whether soil fertility reserves are being replenished, maintained, or depleted over time. A negative balance signals net nutrient mining, implying that crop removal, erosion, leaching, and gaseous losses collectively exceed the inputs from fertilisers, organic matter, atmospheric deposition, and biological fixation (Smaling & Fresco, 1993). Such negative balances, if sustained over multiple cropping seasons, inevitably lead to declining soil fertility, reduced crop yields, and the cascading social and economic consequences that accompany them.

The Bundelkhand region of north-central India represents one of the most compelling—and neglected—case studies for applying the nutrient balance sheet framework. Spanning approximately 71,000 square kilometres across the southern districts of Uttar Pradesh and the northern districts of Madhya Pradesh, Bundelkhand is a region of extraordinary ecological diversity but also profound agricultural vulnerability. Its semi-arid climate, shallow and rocky soils, erratic and declining rainfall, and limited irrigation infrastructure have historically constrained agricultural intensification. At the same time, the region supports a large rural population whose livelihoods depend almost entirely on rain-fed agriculture. The combination of intensive land use, poor soil conservation practices, and severely imbalanced nutrient management has accelerated the depletion of soil fertility to a degree that threatens the sustainability of agriculture across the region (Srinivasarao et al., 2013).

Nutrient imbalances in Indian agriculture are well documented at the national level. Pathak et al. (2010) demonstrated that while the application of nitrogen-containing fertilisers has increased substantially since the Green Revolution, the use of phosphorus and especially potassium fertilisers has lagged considerably behind crop demand, resulting in progressively negative soil potassium and phosphorus balances in many parts of India. However, the national-level analyses often mask the acute regional disparities that exist within countries as large and ecologically diverse as India. Bundelkhand, with its specific combination of soil types, cropping systems, input access constraints, and climatic stressors, demands a region-specific nutrient balance analysis to understand the true extent of fertility depletion and to devise actionable strategies for its reversal.

The significance of nutrient balance assessments extends well beyond agronomic diagnostics. They are increasingly recognised as policy tools for targeting fertiliser subsidies, designing watershed management interventions, guiding extension advisory services, and evaluating the sustainability of agricultural transitions over time. The Food and Agriculture Organization of the United Nations has consistently advocated for the use of nutrient balance methodologies at various spatial scales—from the farm to the national level—as components of broader sustainable land management strategies (FAO, 2004; Roy et al., 2003). In the Indian context, where government expenditure on fertiliser subsidies is enormous but the spatial efficiency of nutrient application remains poor, the nutrient balance sheet approach offers a cost-effective framework for improving the targeting and effectiveness of public investments in soil health.

Despite the growing body of literature on nutrient balances in global and Indian agriculture, there exists a notable paucity of dedicated review articles that synthesise the available evidence specifically for the Bundelkhand region. This gap is particularly significant given Bundelkhand's unique socio-ecological character—straddling the divide between the Indo-Gangetic Plain and the Deccan Plateau, experiencing recurrent droughts, and facing acute challenges of rural out-migration and agrarian distress. The region has been the subject of numerous government interventions, including special developmental packages and integrated watershed management programmes, yet the nutrient dimension of soil fertility management remains inadequately addressed in both academic discourse and policy implementation.

The present review attempts to bridge this gap by consolidating existing knowledge on the nutrient balance sheet approach and its application to the specific agro-ecological conditions of Bundelkhand. It draws upon peer-reviewed literature, government reports, and international agency assessments to construct a comprehensive understanding of nutrient input–output dynamics, soil fertility status, management options, and policy dimensions relevant to the region.

1.1 Scope and Objectives of the Review

The scope of this review is deliberately focused on the Bundelkhand region as a specific agro-ecological unit, whilst drawing upon the broader scientific literature on nutrient balance methodologies, soil fertility management, and dryland agricultural systems to contextualise the regional evidence. The review does not restrict itself to any single nutrient or cropping system but considers the full spectrum of macro and micronutrients relevant to the major crop rotations practised in Bundelkhand, including wheat–gram, sorghum–wheat, and fallow–wheat systems.

The primary objectives of the review are: first, to describe the agro-ecological context and soil resource base of the Bundelkhand region as background for understanding nutrient dynamics; second, to elucidate the conceptual and methodological foundations of the nutrient balance sheet approach; third, to assess the available evidence on soil fertility status and nutrient input–output balances in Bundelkhand; fourth, to evaluate integrated nutrient management strategies appropriate for the region's constraints and opportunities; fifth, to examine the roles of climate, water, and land degradation in modulating nutrient balances; and sixth, to identify policy and institutional mechanisms that could facilitate the adoption of nutrient balance-based soil fertility management in Bundelkhand.

2. Methods for Literature Selection

This review was conducted as a narrative review rather than a systematic review. This choice was deliberate and is justified by the breadth and interdisciplinary nature of the subject matter, which encompasses soil science, agronomy, ecology, hydrology, and policy analysis. A systematic review, with its strict inclusion criteria and quantitative synthesis requirements, would have been insufficiently flexible to accommodate the diverse methodological approaches, spatial scales, and disciplinary perspectives that are necessary for a holistic understanding of nutrient balance management in Bundelkhand. A narrative approach allowed for the exercise of expert judgement in selecting and synthesising literature that collectively addresses the complexity of the topic.

Literature was identified through searches of major academic databases including Web of Science, Scopus, Google Scholar, and PubMed. Search strings were constructed around key terms including "nutrient balance," "soil fertility," "Bundelkhand," "dryland agriculture India," "nitrogen phosphorus potassium balance India," "integrated nutrient management," "soil organic matter India," "soil degradation India," and "semi-arid soil fertility." Searches were conducted with a primary focus on publications from the year 2000 onwards, ensuring that the evidence base reflects recent advances in soil science and nutrient management research. However, classic foundational works predating 2000—particularly those establishing the theoretical framework of the nutrient balance approach—were also included where they remain scientifically indispensable.

Inclusion criteria required that sources be published in peer-reviewed academic journals or as technical bulletins from internationally recognised bodies such as the Food and Agriculture Organization. Conference proceedings, non-peer-reviewed grey literature, and book chapters were excluded to maintain the scientific rigour of the evidence base. Bundelkhand-specific studies were preferentially included, supplemented by research on comparable agro-ecological systems in semi-arid India and the broader developing world where region-specific evidence was sparse.

3. The Bundelkhand Region: Agro-ecological Context and Soil Resources

The Bundelkhand region occupies the north-central portion of the Indian subcontinent, situated between the Yamuna River to the north and the Vindhyan ranges to the south. Administratively, the region comprises thirteen districts—seven in Uttar Pradesh (Jhansi, Lalitpur, Banda, Chitrakoot, Hamirpur, Mahoba, and Jalaun) and six in Madhya Pradesh (Sagar, Damoh, Tikamgarh, Chhatarpur, Panna, and Datia). The total geographical area of approximately 71,000 square kilometres supports a largely rural population with an economy heavily dependent on agriculture and allied activities. The region is widely recognised as one of the most economically underdeveloped and ecologically stressed areas of India, characterised by persistent poverty, widespread malnutrition, and recurrent agrarian crises driven by drought and crop failure.

Climatically, Bundelkhand falls within the semi-arid zone, with mean annual rainfall ranging from approximately 700 to 1,100 millimetres, of which a disproportionate share falls during the South-West Monsoon season (June to September). Rainfall distribution is notoriously erratic, with the coefficient of variation commonly exceeding thirty per cent, and the region has experienced multiple consecutive drought years in the early twenty-first century. Temperatures fluctuate widely between the hot dry summer months, when they can exceed 45°C, and the relatively cool winter, which constitutes the principal season for many field crops including wheat and pulses. This climatic volatility creates a highly unpredictable agricultural environment that discourages investment in soil improvement and long-term fertility management (Rockström et al., 2009).

Geologically, Bundelkhand is underlain predominantly by ancient Precambrian granites and gneisses, with patches of Vindhyan sandstone and limestone, and pockets of black cotton soil over basaltic parent material in the southern and south-western parts of the region. This geological diversity gives rise to a complex mosaic of soil types. The dominant soils include the shallow and gravelly red-yellow soils (Alfisols and Inceptisols) that are characteristic of the granite–gneiss terrain, deep black cracking clays (Vertisols) of basaltic origin, and mixed red and black soils in transitional zones. The red soils, though widely distributed, are generally low in inherent fertility, with limited water-holding capacity, susceptibility to surface sealing, and low organic matter content. The Vertisols, despite their higher clay content and cation exchange capacity, are difficult to manage due to their swelling–shrinking behaviour and associated tillage challenges (Wani et al., 2003).

The shallow soils of the upland areas are especially vulnerable to water erosion, which during high-intensity monsoon events can strip the topsoil of its most biologically active and nutrient-rich layer. Sharda et al. (2010) estimated that production losses attributable to water erosion in rainfed areas of India are enormous, and Bundelkhand, with its undulating terrain, sparse vegetative cover, and rocky outcrops, is particularly susceptible to this process. Soil organic carbon levels across the region are generally very low, often below 0.5 per cent in many surface horizons, which substantially reduces the capacity of these soils to retain nutrients, support microbial activity, and buffer against the chemical degradation associated with acidification or alkalisation (Srinivasarao et al., 2009).

The principal cropping systems of Bundelkhand include the wheat–gram (Triticum aestivum–Cicer arietinum) rotation in the rabi season, the kharif cultivation of sorghum (Sorghum bicolor), pearl millet (Pennisetum glaucum), sesame (Sesamum indicum), and urd bean (Vigna mungo), and in irrigated pockets, the sugarcane–wheat rotation. Oilseed crops, especially mustard (Brassica juncea) and linseed (Linum usitatissimum), are traditionally important. Fallow periods, especially in the kharif season, are common in many parts of the region due to moisture stress, which further limits biomass return to the soil and exacerbates organic matter depletion. The absence of large-scale irrigation infrastructure means that the overwhelming majority of Bundelkhand's agricultural production remains rain-fed and thus highly susceptible to seasonal moisture deficits (Srinivasarao et al., 2013).

Livestock farming is integral to the agrarian economy of Bundelkhand, and the use of cattle dung and farmyard manure has historically constituted a significant pathway of nutrient recycling. However, declining herd sizes, the diversion of dung for fuel, and reduced availability of crop residues as fodder have progressively weakened this organic nutrient cycle, further contributing to negative nutrient balances. The region's geomorphological complexity, soil diversity, and limited data infrastructure present significant challenges for conducting precise, spatially resolved nutrient balance assessments, underscoring the need for both improved data collection systems and the application of robust methodological frameworks such as the nutrient balance sheet approach.

4. Concept and Theoretical Framework of the Nutrient Balance Sheet Approach

4.1 Historical Development and Methodological Foundations

The nutrient balance sheet approach has its intellectual origins in the classical agronomic tradition of comparing nutrient inputs and outputs across agricultural systems to assess whether soil fertility is being maintained or depleted. The formalisation of this approach as a systematic methodology gained momentum in the late twentieth century, particularly through the work of Smaling and Fresco (1993), who developed the NUTMON (Nutrient Monitoring) framework as a decision-support model for monitoring nutrient balances under agricultural land use. This framework decomposed nutrient flows into five input categories—mineral fertilisers, organic materials, atmospheric deposition, biological nitrogen fixation, and sedimentation—and five output categories—crop removal, residue removal, leaching, gaseous losses, and erosion. The NUTMON approach, initially developed and applied in sub-Saharan Africa, subsequently provided the theoretical architecture for nutrient balance analyses across a wide range of agro-ecological contexts globally (FAO, 2004).

A significant advance in the methodology came with the development of the soil nutrient balance framework articulated in a series of technical bulletins by the Food and Agriculture Organization (Roy et al., 2003; FAO, 2004). These publications provided standardised protocols for compiling nutrient balance estimates at different spatial scales—from the individual farm to the national level—and offered conversion factors, default values, and methodological guidelines for data-limited environments. At its core, the nutrient balance is computed as the algebraic difference between the sum of all nutrient inputs and the sum of all nutrient outputs for a defined system boundary over a defined time period. A positive balance indicates net accumulation of nutrients in the soil; a balance approximating zero indicates maintenance of the existing fertility status; and a negative balance indicates net depletion of soil fertility reserves.

The simplicity of this conceptual framework belies the considerable methodological challenges involved in its accurate application. Nutrient input and output pathways are numerous, spatially heterogeneous, and often difficult to quantify without site-specific data. Atmospheric nitrogen deposition, for example, varies greatly with proximity to industrial sources and vegetation type; biological nitrogen fixation depends on soil pH, legume species, and rhizobial populations; nutrient losses through leaching depend on soil texture, rainfall intensity, and subsoil chemistry. Despite these challenges, the nutrient balance approach has proven invaluable as a diagnostic and planning tool, particularly in regions where detailed soil fertility data are lacking but where the consequences of fertility decline are most severe (Vitousek et al., 2009).

4.2 Nutrient Input and Output Pathways

Nutrient inputs to agricultural systems in the Bundelkhand context can be grouped into four principal categories. Mineral fertilisers represent the most quantifiable and directly manageable input, encompassing the application of urea, diammonium phosphate, muriate of potash, and other straight or complex fertilisers. Organic inputs include farmyard manure, compost, green manures, and crop residue incorporation, all of which contribute not only macronutrients but also secondary and micronutrients and, crucially, organic matter that supports the biological and physical functioning of the soil (Chivenge et al., 2011). Biological nitrogen fixation through legume–Rhizobium symbioses constitutes an ecologically important nitrogen input pathway, particularly in cropping systems that include gram, lentil, urd bean, or other leguminous species. Finally, atmospheric deposition of nitrogen—comprising both wet deposition in rainfall and dry deposition of particulate and gaseous species—though individually small, can be non-trivial at the annual scale, particularly in areas with significant ambient nitrogen pollution from agricultural and combustion sources (Gruber & Galloway, 2008).

On the output side, the removal of nutrients in harvested crop biomass is typically the dominant loss pathway and the most straightforward to quantify using crop production statistics and published harvest index and nutrient concentration data. However, nutrient losses through other pathways are equally consequential for the overall nutrient balance. Leaching of nitrate and other mobile ions below the root zone is particularly significant during high-intensity rainfall events on sandy or coarse-textured soils, representing both a direct fertility loss and a potential water quality concern (Ladha et al., 2005). Gaseous nitrogen losses through volatilisation of ammonia—especially from urea-containing fertilisers applied to calcareous or alkaline soils—and through denitrification under waterlogged conditions, can be substantial and are often underestimated in farm-scale nutrient budgets. Nutrient losses through soil erosion are highly significant in Bundelkhand given the region's topography and rainfall characteristics; the selective removal of fine particles and organic matter in eroded material means that erosion disproportionately depletes the most fertile and nutrient-rich fraction of the topsoil (Lal, 2009; Sharda et al., 2010).

The importance of understanding these pathways collectively rather than in isolation cannot be overstated. Focusing exclusively on fertiliser inputs whilst ignoring erosion losses, or accounting for crop removal whilst neglecting organic additions, produces nutrient balance estimates that are misleading and potentially counterproductive as a basis for management decisions. It is this integrative, systems-level perspective that constitutes the core strength of the nutrient balance sheet methodology as a framework for sustainable soil fertility management.

5. Soil Fertility Status in the Bundelkhand Region

5.1 Macronutrient Status

The assessment of soil fertility across the Bundelkhand region reveals a landscape characterised by widespread and multi-nutrient deficiency, compounded by decades of extractive agricultural practices and insufficient nutrient replenishment. Nitrogen deficiency is near-universal in Bundelkhand soils. The inherently low organic carbon content of the dominant red and shallow soils translates directly into limited mineralisation of organic nitrogen, rendering these soils incapable of sustaining nitrogen supply to crops through biological cycling alone. The use of chemical nitrogenous fertilisers, whilst having increased modestly over recent decades, remains well below the recommended levels for major crops, and the efficiency of applied nitrogen is further reduced by the high losses through volatilisation and surface runoff characteristic of the region's calcareous and degraded soils (Ladha et al., 2005).

Phosphorus status in Bundelkhand soils is also broadly deficient, though with considerable spatial variability depending on parent material and management history. The red soils derived from granites and gneisses typically exhibit strong phosphorus fixation due to the presence of aluminium and iron oxides, which reduce the plant availability of applied phosphate through adsorption reactions. As a result, the efficiency of applied phosphate fertiliser is substantially lower than its theoretical potential, and cumulative phosphorus deficits have developed in soils receiving below-recommended phosphorus doses over extended periods (Sattari et al., 2012). The legacy phosphorus stocks that have accumulated in better-managed soils in more intensified parts of India are largely absent in Bundelkhand, meaning that crops here have minimal buffer against year-to-year variability in phosphate supply.

Potassium status presents a more complex and variable picture across the region. The Vertisols of the southern Bundelkhand areas, derived from basaltic parent material, are naturally well-endowed with potassium due to their illitic clay mineralogy, and potassium deficiency in these soils may not be immediately apparent even under sustained cropping. In contrast, the red soils and sandy alluvial soils of the central and northern parts of the region have lower potassium-supplying power and are increasingly showing evidence of potassium depletion under intensive cereal cultivation. The situation is worsened by the near-complete absence of potassic fertiliser application in most of Bundelkhand, where many farmers either do not use potassic fertilisers at all or use them in quantities far below agronomic recommendations, perpetuating negative potassium balances (Zörb et al., 2014; Pathak et al., 2010).

Sulphur deficiency has emerged as an increasingly significant constraint in Indian agriculture, and Bundelkhand is no exception. The shift from sulphur-containing fertilisers such as single superphosphate and ammonium sulphate towards cleaner but sulphur-free formulations such as urea and triple superphosphate has reduced incidental sulphur inputs across Indian agriculture. In Bundelkhand, where oilseed crops, which are particularly sensitive to sulphur deficiency, form part of many rotations, the inadequate sulphur supply is increasingly reflected in reduced oil quality and yield (Bindraban et al., 2015).

5.2 Secondary and Micronutrient Status

Micronutrient deficiencies in Bundelkhand soils are widespread and represent a growing constraint on crop productivity that has received insufficient attention in regional agricultural development planning. Zinc is the most commonly reported micronutrient deficiency in Indian soils, and Bundelkhand, with its calcareous and high-pH soils in parts of the region, is particularly susceptible to zinc immobilisation. The fixation of zinc in alkaline soils through the formation of zinc carbonate and zinc silicate compounds reduces its plant availability well below critical thresholds, causing widespread visual deficiency symptoms—including bronzing of leaves, stunted growth, and poor grain set—in wheat, sorghum, and grain legumes (Meena et al., 2017). Iron and manganese deficiencies have also been reported in the calcareous soils of the region, though their agronomic significance is less consistently documented.

Boron deficiency has been identified as a critical constraint in pulse crops, particularly in gram and lentil, which are staple food and income crops for smallholder farmers in Bundelkhand. Boron is essential for pollen viability and seed set, and its deficiency under conditions of low organic matter and coarse soil texture leads to significant yield losses that are rarely diagnosed correctly at the farm level. The status of molybdenum, copper, and other trace elements in Bundelkhand soils has been less comprehensively studied, but available evidence suggests that multi-micronutrient deficiency is more the rule than the exception in the region's degraded soils (FAO & ITPS, 2015).

The widespread multi-nutrient deficiency of Bundelkhand soils is not merely a reflection of inherent pedogenic limitations but is substantially the product of long-term extractive management practices that have progressively depleted both the organic matter pool and the inorganic nutrient reserves. The low application rates of organic manures, the near-complete absence of secondary and micronutrient fertilisation, and the continuous cropping of nutrient-demanding cereals and oilseeds without adequate replenishment have collectively created a deeply negative nutrient balance that, if not corrected, will continue to erode the region's agricultural productivity and the food security of its rural population (Lal, 2004; Srinivasarao et al., 2013).

6. Nutrient Input–Output Dynamics in Bundelkhand Agriculture

6.1 Nutrient Inputs: Fertilisers, Organic Amendments, and Atmospheric Deposition

An accurate assessment of nutrient inputs in Bundelkhand agriculture must account for the full range of intentional and incidental nutrient additions to the farming system. Mineral fertiliser application represents the most significant and measurable intentional input, yet fertiliser consumption in Bundelkhand remains substantially below the national average and far below the recommended doses for major crops. The reasons for this under-application are complex and interrelated, including the high cost of fertilisers relative to crop prices, the limited access to credit among smallholder farmers, the risk aversion associated with uncertain rainfall and low expected returns, and the poor extension support available to farmers in the region. The consequence of systematic under-fertilisation is a persistent structural deficit in nutrient supply that, when viewed through the lens of the balance sheet framework, is the primary driver of negative nutrient balances (Stewart et al., 2005).

The application of farmyard manure and crop residues constitutes the principal organic nutrient pathway in traditional Bundelkhand agriculture. Historically, the integration of livestock—primarily cattle and goats—into the cropping system provided a mechanism for partial nutrient recycling, with dung collected from stabled animals applied to fields before the kharif season. However, this organic nutrient cycle has weakened considerably over the past two to three decades. Declining cattle populations due to shrinking fodder availability, the diversion of dung to fuel use in the absence of alternative cooking energy, and the shift towards shorter-duration pulses and vegetables that leave little crop residue, have all reduced the organic matter inputs to Bundelkhand soils. Estimates suggest that the average farmyard manure application in dryland areas of central India rarely exceeds two to three tonnes per hectare per annum, compared to the recommended ten to fifteen tonnes, resulting in a substantial shortfall in organic matter replenishment (Timsina, 2018; Bhattacharyya et al., 2008).

Biological nitrogen fixation through leguminous crops in the rotation represents a valuable internal nitrogen input that, if properly managed, can meaningfully offset the need for mineral nitrogen. The pulse crops traditionally grown in Bundelkhand—gram, lentil, urd bean, and pigeon pea—are all capable of fixing atmospheric nitrogen through symbiosis with Rhizobium and Bradyrhizobium species. However, the effectiveness of this fixation is contingent upon the presence of effective rhizobial strains in the soil, adequate soil pH, and freedom from the moisture stresses that can severely curtail legume nodulation and nitrogen fixation. Given the frequency of drought stress in Bundelkhand, biological nitrogen fixation is highly variable and unreliable as a nutrient input pathway, and its contribution to the system nutrient balance is likely far below the potential values measured under well-managed experimental conditions (Meena et al., 2017).

Atmospheric nitrogen deposition, though modest in arid and semi-arid regions compared to urban and industrial areas, provides a background nitrogen input that is ecologically important in heavily nitrogen-depleted systems. Estimates for rural India suggest wet plus dry deposition of nitrogen in the range of five to fifteen kilograms per hectare per year, depending on proximity to agricultural emission sources and the intensity of biomass burning (Gruber & Galloway, 2008). In Bundelkhand, where stubble burning and biomass combustion are common during the kharif–rabi transition, local nitrogen deposition from smoke could be marginally higher than background levels, though quantitative data for the region are scarce.

6.2 Nutrient Losses: Crop Removal, Erosion, and Leaching

Nutrient losses through crop removal represent the single largest and most predictable output in the Bundelkhand nutrient balance. The combination of harvesting grain, stover, and in many cases the entire shoot biomass from crops leaves the soil with a substantial net extraction of nitrogen, phosphorus, and potassium at each harvest. For the dominant wheat–gram rotation, the combined nitrogen removal in grain and straw can amount to 120 to 150 kilograms per hectare per annum under moderately productive conditions, a level of extraction that vastly exceeds the combined inputs from fertilisers, manures, and biological fixation in most Bundelkhand farms (Pathak et al., 2010). The complete removal of crop residues for fodder and fuel, rather than returning them to the soil, further amplifies the effective nutrient output from the system.

Soil erosion constitutes the second major nutrient loss pathway and is of particular significance in Bundelkhand's undulating terrain. The vulnerability of the region's shallow red soils to splash erosion, rill formation, and gully development during intense monsoon events means that substantial quantities of topsoil—and with it, the organic matter, nitrogen, phosphorus, and micronutrient reserves concentrated in the surface horizon—are lost annually. The nutrient value of eroded topsoil is considerably higher than that of the subsoil exposed after erosion, as organic matter, clay particles, and adsorbed nutrients are disproportionately represented in fine-fraction eroded material. Lal (2009) estimated that soil erosion globally imposes severe constraints on nutrient supply, and studies in comparable dryland environments of India suggest that annual topsoil losses can reach several tonnes per hectare in degraded hillslope areas, translating into ecologically and economically significant nutrient losses (Sharda et al., 2010).

Leaching losses, whilst less visually dramatic than erosion, are nonetheless significant under specific soil and climatic conditions that are relevant to parts of Bundelkhand. The sandy and coarse-textured soils of the alluvial plains and river valley areas are particularly susceptible to nitrate leaching during and immediately following heavy monsoon rainfall events, when the rate of water percolation exceeds the rate of microbial nitrogen immobilisation or plant uptake. The resulting leaching of nitrate below the root zone represents a permanent removal of nitrogen from the agricultural system, with the additional consequence of contributing to groundwater contamination (Ladha et al., 2005). Potassium leaching, whilst generally less significant in clay-dominated soils, can be non-trivial in the coarser-textured soils of the region, particularly where potassium inputs are low and exchangeable potassium reserves are already depleted (Zörb et al., 2014).

Gaseous nitrogen losses through ammonia volatilisation and denitrification, whilst less directly measurable than other output pathways, are agronomically important and ecologically consequential. Urea, which is the predominant nitrogenous fertiliser used in India including Bundelkhand, is highly susceptible to hydrolysis and ammonia volatilisation when applied to the surface of alkaline or calcareous soils without incorporation, a practice common in resource-poor smallholder farming systems. Estimates for volatilisation losses from surface-applied urea in semi-arid Indian soils range widely, but figures of twenty to forty per cent of applied nitrogen are not uncommon under unfavourable conditions, implying that a substantial fraction of the fertiliser nitrogen never enters the crop–soil system (Ladha et al., 2005).

7. Nutrient Balance Assessment: Evidence and Implications

The compilation of nutrient balance estimates for Bundelkhand, integrating the input and output pathways described above, consistently points to a picture of severe and multi-nutrient negative balance across the dominant farming systems of the region. Whilst precise and spatially resolved balance estimates for Bundelkhand as a whole are constrained by data limitations, the available evidence at the regional and comparable agro-ecological scale indicates that nitrogen, phosphorus, and potassium balances are all negative, with potassium exhibiting the most extreme deficit in many soil types due to the near-absence of potassic fertiliser inputs (Pathak et al., 2010).

At the national level, analyses by Pathak et al. (2010) revealed a more nuanced picture of India's nutrient balance: nitrogen and phosphorus balances were, in aggregate, slightly positive at the national scale—reflecting the influence of heavily subsidised urea and the modest build-up of phosphorus in intensively cultivated regions—whilst potassium showed a significantly negative balance of approximately 3.3 million tonnes, reflecting chronic under-application of potassic fertilisers across the country. These nationally aggregated figures, however, mask profound regional disparities. In chronically under-fertilised, rain-fed regions such as Bundelkhand, where fertiliser inputs remain well below the national average, nitrogen and phosphorus inputs are frequently insufficient to offset crop removal, creating effectively negative balances for all three macronutrients at the local level. Vitousek et al. (2009) situated the Indian nutrient balance problem within a global context of nutrient imbalances in developing-country agriculture, arguing that the simultaneous occurrence of nutrient overuse in some areas and severe nutrient depletion in others represents one of the defining environmental management challenges of the current era.

The negative nutrient balances in Bundelkhand have compounding effects on soil quality beyond simple fertility depletion. As soil organic matter is progressively mineralised without sufficient replacement, the soil's physical structure deteriorates: aggregate stability declines, bulk density increases, and water infiltration is reduced, making the soil simultaneously more prone to surface crusting and runoff during rainfall and more vulnerable to drought stress during dry periods. This degradation of soil physical properties amplifies the losses through erosion and runoff, creating a self-reinforcing cycle of fertility decline and structural degradation that is exceedingly difficult to reverse without sustained and targeted intervention (Lal, 2004; Six et al., 2002).

The consequences of persistent negative nutrient balances for crop yields in Bundelkhand are tangible and well recognised at the farm level. Average wheat yields in the region are typically in the range of 1.5 to 2.5 tonnes per hectare, compared to a national average of approximately 3.4 tonnes per hectare and an attainable yield well in excess of five tonnes per hectare under optimal management. Similarly, gram yields in Bundelkhand are generally 0.6 to 1.0 tonnes per hectare under rain-fed conditions, with significant year-to-year variability associated with rainfall timing and distribution. This yield gap between actual and attainable levels is attributable to multiple interacting factors—including water stress, pest and disease pressure, and varietal limitations—but soil fertility deficiency, as revealed by nutrient balance analyses, is consistently identified as a primary limiting factor (Srinivasarao et al., 2013; Wani et al., 2003).

A further dimension of the nutrient balance problem in Bundelkhand is the qualitative imbalance among nutrients, which is as important as the quantitative deficit. The heavy subsidisation of urea in India has led to patterns of fertiliser use that are heavily skewed towards nitrogen, with phosphorus and potassium applications lagging well behind. This imbalance creates sub-optimal stoichiometric ratios of nutrients in the soil solution, reducing the efficiency with which each individual nutrient is utilised by the crop. For example, excessive nitrogen application in the absence of adequate phosphorus and potassium can stimulate vegetative growth whilst producing hollow grain fill and structural weaknesses, ultimately failing to translate nitrogen inputs into proportional yield gains (Stewart et al., 2005; Bindraban et al., 2015). In Bundelkhand, where the prevailing N:P:K application ratio is already skewed—in many cases with negligible potassium application—this qualitative imbalance compounds the quantitative deficiency to produce crop performance well below what could be achieved with a more balanced nutrient management approach.

8. Integrated Nutrient Management Strategies for Nutrient Balance Restoration

8.1 Organic Matter and Compost Application

The restoration of positive or near-zero nutrient balances in Bundelkhand's depleted soils requires a multi-pronged integrated nutrient management strategy that combines mineral fertilisation with organic matter management, biological inputs, and structural interventions to reduce nutrient losses. No single approach is sufficient in isolation; the complexity of the nutrient balance problem demands an equally complex and context-specific management response.

The augmentation of soil organic matter through the application of farmyard manure, compost, vermicompost, and other organic materials is the most fundamental building block of any soil fertility restoration programme in Bundelkhand. Organic materials contribute not only to the macronutrient supply through mineralisation but also to the sustained release of secondary nutrients and micronutrients, the improvement of soil physical properties, and the stimulation of soil microbial activity that drives nutrient cycling processes. Chivenge et al. (2011), in a comprehensive meta-analysis, demonstrated that the combined application of organic and mineral nutrient sources consistently outperformed either alone in terms of crop productivity and nutrient use efficiency, suggesting that the synergistic effects of organic–inorganic nutrient combinations are of critical practical importance. This finding is particularly relevant for Bundelkhand, where the low inherent organic matter of the soils limits the efficiency of mineral fertilisers applied in isolation (Bhattacharyya et al., 2008).

The production and application of compost at a scale relevant to improving regional nutrient balances requires both technical support and a rethinking of organic resource management at the household and community level. Waste biomass from crops, forest residues, household organic wastes, and even press mud from jaggery production—all available in significant quantities in parts of Bundelkhand—could be composted and applied to soils to substantially increase organic carbon and nutrient inputs. The challenge is less one of material availability than of the logistical, economic, and social barriers to scaling compost production and distribution in the resource-constrained farming communities of the region. The FAO and ITPS (2015) report on the status of the world's soil resources emphasised that maintaining and enhancing soil organic matter is a cross-cutting priority for reversing the trajectory of soil degradation in South Asian dryland systems, a conclusion of particular relevance to Bundelkhand.

8.2 Green Manuring and Biofertilisers

Green manuring with fast-growing legumes such as dhaincha (Sesbania bispinosa), sunnhemp (Crotalaria juncea), and cowpea (Vigna unguiculata) is a time-honoured agronomic practice in India that can substantially improve soil nitrogen status whilst also adding organic matter and improving soil physical conditions. The incorporation of green manure biomass at the appropriate stage of growth—before peak flowering, when the biomass is still succulent and the carbon-to-nitrogen ratio is favourable for rapid mineralisation—can contribute sixty to one hundred and twenty kilograms of nitrogen per hectare per season, effectively substituting for a significant proportion of the mineral nitrogen requirement of the following cereal crop (Timsina, 2018). In the context of Bundelkhand's kharif–rabi rotation, the sowing of a short-duration green manure crop during the early or mid-kharif season, particularly in years when moisture conditions do not favour food crop production, represents a rational strategy for nitrogen input, organic matter accretion, and risk management.

Biofertilisers—preparations of beneficial microorganisms including nitrogen-fixing bacteria (Rhizobium, Azospirillum, Azotobacter), phosphate-solubilising bacteria and fungi, and mycorrhizal inoculants—represent a low-cost, ecologically sound complement to chemical fertilisation that has been substantially underpromoted in Bundelkhand's agricultural development programmes. The mechanisms through which plant beneficial rhizospheric microorganisms enhance nutrient availability include biological nitrogen fixation, the solubilisation of inorganic phosphate through the production of organic acids and enzymes, the chelation of micronutrients, and the production of growth-promoting substances that enhance root architecture and nutrient uptake efficiency (Meena et al., 2017). The effectiveness of biofertiliser applications is, however, context-dependent and requires attention to inoculant quality, soil pH, moisture, and the compatibility of microbial strains with local soil conditions. In Bundelkhand, where extension capacity is limited, the quality control and distribution of effective biofertiliser formulations remain significant challenges to widespread adoption.

8.3 Site-Specific Nutrient Management

Site-specific nutrient management represents a precision approach to fertiliser recommendation that tailors nutrient inputs to the specific soil fertility status and crop nutrient demand of individual fields, rather than applying blanket recommendations across heterogeneous landscapes. This approach has been shown to improve both nutrient use efficiency and economic returns to fertiliser investments by avoiding over-application in already-fertile soils and under-application in deficient ones (Bindraban et al., 2015). In the context of Bundelkhand, where soil fertility varies enormously over short distances due to the complex mosaic of soil types, parent materials, and management histories, the site-specific nutrient management philosophy is particularly relevant, even if its full implementation is constrained by the limited availability of soil testing infrastructure and agronomic advisory services.

Soil test-based fertiliser recommendations, underpinned by a network of soil testing laboratories and farmer advisory systems, are foundational to any operationalisation of the nutrient balance sheet approach at the farm scale. The government of India has recognised this through the Soil Health Card scheme, launched under the National Mission for Sustainable Agriculture, which aims to provide every farmer with information on the fertility status of their soil and appropriate fertiliser recommendations. However, the effective reach of this scheme in Bundelkhand has been hampered by logistical constraints, limited laboratory capacity, and the challenge of translating test results into actionable and affordable management recommendations for smallholder farmers. Strengthening the institutional infrastructure for soil testing and nutrient advisory services in Bundelkhand is therefore a prerequisite for operationalising the nutrient balance framework at the scale required to address regional fertility decline (Vanlauwe et al., 2010).

The importance of integrated soil fertility management—defined as the combined use of mineral fertilisers, organic inputs, and improved germplasm, adapted to local conditions—as a unifying framework for sustainable nutrient management in resource-constrained environments has been strongly advocated by international research institutions (Vanlauwe et al., 2010). This concept acknowledges that neither organic nor mineral nutrient sources alone can sustainably maintain soil fertility and crop productivity in depleted tropical and sub-tropical soils, and that their intelligent combination, informed by nutrient balance principles, offers the most promising pathway to restoring positive or near-zero nutrient balances in regions like Bundelkhand. Srinivasarao et al. (2013) similarly concluded from extensive work in Indian dryland systems that the integration of organic and inorganic nutrient sources, combined with soil water conservation, represents the most effective strategy for reversing soil organic carbon depletion and restoring productive capacity in degraded dryland soils.

9. Role of Climate, Water, and Land Degradation in Nutrient Balance

The nutrient balance of Bundelkhand's agricultural soils cannot be understood in isolation from the overarching climatic and hydrological context within which the region's farming systems operate. The interaction of climate variability, water availability, and land degradation creates a set of conditions that substantially modulate nutrient dynamics and frequently amplify the negative nutrient balances resulting from management-related factors.

Rainfall variability in Bundelkhand is a fundamental driver of interannual fluctuations in nutrient balances. In years of adequate and well-distributed rainfall, crop production is higher, crop nutrient uptake is more efficient, and the proportion of applied fertiliser that contributes to yield—rather than being lost through unproductive pathways—is greater. Conversely, in drought years, reduced crop growth and nutrient uptake mean that applied fertilisers are more likely to be lost through leaching, erosion, or remaining as residual inorganic nitrogen that is susceptible to denitrification in subsequent waterlogged events (Rockström et al., 2009). The resulting high year-to-year variability in nutrient use efficiency makes rational nutrient management under rain-fed conditions a particularly complex challenge that the nutrient balance sheet framework must accommodate through scenario-based and probabilistic approaches rather than single-point estimates.

Soil water conservation measures—including contour bunding, check dams, farm ponds, and conservation tillage—are directly relevant to nutrient balance management because they determine the extent to which rainfall is retained within the root zone rather than lost as runoff. When more water is retained in the soil, nutrient uptake efficiency is improved, leaching losses are reduced, and the economic return to fertiliser investment is enhanced. The complementarity between water harvesting interventions and soil fertility management is thus high, and their integrated planning within a nutrient balance framework offers a powerful approach to simultaneously addressing water and nutrient constraints in Bundelkhand (Wani et al., 2003; Srinivasarao et al., 2013).

Land degradation in Bundelkhand, manifested as soil erosion, ravine formation, surface sealing, and the progressive conversion of cultivated land to wasteland, represents a major and spatially extensive threat to the region's agricultural potential. The FAO and ITPS (2015) report on the status of the world's soil resources identified South Asia as one of the regions most severely affected by soil degradation, with nutrient depletion and erosion cited as the dominant degradation processes. In Bundelkhand, the degradation of agricultural land through ravine formation—particularly along the Ken, Betwa, and Dhasan river systems—has permanently removed large areas from agricultural production and created highly erodible land peripheries that act as sources of continued sediment and nutrient export. The restoration of degraded lands in Bundelkhand through vegetative cover establishment, terracing, and agroforestry is thus not only an ecological imperative but also a prerequisite for achieving sustainable nutrient balances across the region's agricultural landscape.

The interaction of land degradation with nutrient balance dynamics is further mediated through the role of soil organic carbon. Soil organic carbon functions as the engine of soil fertility, regulating nitrogen mineralisation, supporting microbial diversity, improving soil structure, and enhancing the water-holding capacity that is critical for nutrient use efficiency under rain-fed conditions. The loss of organic carbon through erosion, over-tillage, and inadequate organic matter return creates a downward spiral in which reduced organic carbon leads to poorer soil physical and biological functioning, which in turn reduces the efficiency of nutrient cycling and the ability of the soil to sustain productivity under environmental stress (Six et al., 2002; Lal, 2004). Restoring soil organic carbon levels in Bundelkhand through organic amendment, green manuring, and conservation management is therefore a cross-cutting priority that simultaneously addresses nutrient balance, water balance, and land degradation concerns. Srinivasarao et al. (2009) documented systematically low soil organic carbon stocks in diverse Indian dryland soils across different soil types and rainfed production systems, confirming that organic carbon depletion is a pervasive constraint on biological functioning and productivity in the semi-arid tropics, a situation that is directly applicable to the soil conditions prevailing across Bundelkhand.

10. Policy Frameworks and Institutional Dimensions

The translation of nutrient balance sheet insights into practical improvements in soil fertility management in Bundelkhand requires an enabling policy environment and effective institutional mechanisms for knowledge generation, dissemination, and application at the farm level. Historically, Indian agricultural policy has been dominated by a focus on food grain production through input subsidies—particularly for urea—that have distorted nutrient management practices by making nitrogen artificially cheap relative to phosphorus and potassium. The resulting pattern of nitrogen-heavy, phosphorus- and potassium-deficient fertilisation has directly contributed to the imbalanced nutrient application that is reflected in the negative phosphorus and potassium balances documented across Indian agriculture, including in Bundelkhand (Pathak et al., 2010; Stewart et al., 2005).

The Nutrient-Based Subsidy scheme, introduced by the Government of India in 2010, represented an attempt to correct this distortion by linking subsidy rates to the nutrient content of fertilisers rather than providing flat subsidies per bag. However, the exclusion of urea from this framework has undermined its corrective intent, as urea continues to be sold at a heavily subsidised fixed price that makes it far cheaper per kilogram of nitrogen than any alternative. The correction of this policy asymmetry—by either including urea in the framework or by moving towards a price-neutral subsidy that encourages balanced NPK application—is widely recognised as a prerequisite for improving nutrient management efficiency across India (Vitousek et al., 2009; Bindraban et al., 2015).

At the regional and state level, the governments of Uttar Pradesh and Madhya Pradesh have implemented a number of agricultural development programmes in Bundelkhand through special packages, watershed development projects, and national schemes such as the Pradhan Mantri Krishi Sinchayee Yojana and the Rashtriya Krishi Vikas Yojana. These programmes have addressed aspects of soil and water conservation, irrigation expansion, and agricultural diversification, but have generally not incorporated explicit nutrient balance monitoring as a component of programme design or evaluation. Integrating the nutrient balance sheet framework into the monitoring and evaluation systems of such programmes would provide a rigorous, quantitative basis for assessing their impact on soil fertility and for adjusting management recommendations over time (Roy et al., 2003; FAO, 2004).

The World Bank (2008) has emphasised the importance of public investment in agricultural extension and advisory services as a foundation for sustainable agricultural development in regions characterised by smallholder farming systems and limited market access. In Bundelkhand, the capacity of the public extension system to provide soil fertility advisory services based on nutrient balance principles is severely constrained by staff shortages, limited training in soil science and nutrient management, and weak linkages with research institutions. Strengthening this capacity through investment in extension personnel, soil testing infrastructure, and digital advisory platforms represents a high-return public investment that would substantially enhance the ability of Bundelkhand's farmers to translate nutrient balance insights into practical management decisions.

The role of women in soil fertility management in Bundelkhand deserves specific mention. Women perform the majority of manure management, compost production, and crop residue handling tasks in many parts of the region, and their knowledge of traditional organic nutrient management practices is both extensive and historically undervalued. Agricultural development programmes that engage women as co-designers and co-implementers of integrated nutrient management interventions are likely to achieve greater impact and more equitable outcomes than those that target male household heads exclusively. The institutionalisation of women's participation in Farmer Producer Organisations, Krishi Vigyan Kendras, and watershed committees is therefore an important dimension of the enabling environment for sustainable nutrient management in Bundelkhand.

International experience also suggests that participatory nutrient balance monitoring—in which farmers themselves are trained to understand and estimate key nutrient flows on their own farms—can serve as a powerful tool for building awareness, motivating behaviour change, and generating locally relevant data (Vanlauwe et al., 2010). Such participatory approaches, embedded within farmer field school or self-help group structures that are already operating in parts of Bundelkhand, could provide a cost-effective pathway for scaling the nutrient balance approach from the experimental plot to the landscape level. The critical challenge is to move from academic recognition of the nutrient balance crisis to the political will and institutional commitment needed to address it systematically at the regional scale.

11. Conclusions

The nutrient balance sheet approach provides an indispensable analytical and management framework for understanding and addressing the soil fertility crisis confronting agriculture in the Bundelkhand region of north-central India. This review has synthesised evidence from the soil science, agronomy, and agricultural development literature to demonstrate that Bundelkhand's soils are characterised by severe and multi-nutrient deficiencies—encompassing nitrogen, phosphorus, sulphur, zinc, and boron—that are the product of decades of extractive agricultural management, insufficient nutrient replenishment, and relentless soil erosion. The region's dominant farming systems exhibit deeply negative nutrient balances that, if not reversed through concerted management interventions, will continue to erode the productivity foundation upon which the food security and livelihoods of millions of rural inhabitants depend.

The nutrient balance sheet framework, by systematically quantifying all nutrient inputs and outputs within a defined system boundary, provides both a diagnostic tool for revealing the magnitude and nutrient-specific nature of fertility deficits and a planning framework for evaluating the effectiveness of corrective management strategies. The application of this framework in Bundelkhand reveals that negative balances are most severe for potassium and sulphur—nutrients that receive little or no attention in the prevailing fertilisation practices of the region—and that the organic matter pathway, which is critical for sustained nutrient cycling and soil biological functioning, is grossly under-supported in the region's farming systems.

Integrated nutrient management strategies that combine judicious mineral fertilisation with organic matter augmentation, green manuring, biofertiliser application, and soil conservation measures offer a scientifically robust and economically accessible pathway for restoring near-zero or positive nutrient balances in Bundelkhand. The evidence strongly supports the conclusion that no single intervention is sufficient and that the greatest gains—in both yield and nutrient use efficiency—arise from the synergistic combination of organic and inorganic nutrient sources, supported by site-specific management informed by soil testing. The institutionalisation of periodic nutrient balance monitoring as a standard component of agricultural planning and evaluation at the district and watershed level in Bundelkhand is both scientifically justified and practically urgent.

Policy reform—particularly the correction of fertiliser subsidy distortions that incentivise nitrogen over-application whilst discouraging balanced NPK use—is a necessary complement to farm-level management improvements. The full potential of the nutrient balance approach in Bundelkhand can only be realised through coordinated action across scales: from the individual farmer practising integrated nutrient management on their plots, through the village and watershed levels where collective resource management decisions are made, to the state and national levels where agricultural policies, subsidy structures, and public investment priorities are determined. The region's agricultural future depends on the recognition that soil fertility is not merely an agronomic variable but a foundational natural capital asset whose sustainable management is inseparable from the broader goals of rural development, poverty alleviation, and ecological resilience.

12. Limitations

This review is subject to a number of limitations that should be acknowledged when interpreting its findings and conclusions. First, the availability of region-specific, quantitative nutrient balance data for Bundelkhand is highly constrained. The review has necessarily relied in part on evidence from comparable agro-ecological systems elsewhere in India and in semi-arid developing-country contexts, which may not fully capture the specific soil, climatic, and socio-economic conditions of Bundelkhand. The extrapolation of nutrient balance estimates from national-level analyses or from other dryland regions to the Bundelkhand context involves assumptions about the representativeness of those contexts that cannot be fully validated without dedicated regional studies.

Second, as a narrative rather than systematic review, the selection of literature was inevitably shaped by judgements regarding relevance and quality, introducing the possibility of selection bias. The absence of a predefined and exhaustively applied inclusion–exclusion protocol means that some relevant studies may have been inadvertently overlooked, particularly those published in regional or national journals not indexed in the primary databases searched.

Third, the rapidly changing agricultural landscape of Bundelkhand—driven by climate variability, government intervention programmes, the expansion of irrigation through bore wells, and shifting crop preferences—means that some of the published evidence on which this review draws may not fully reflect current conditions on the ground. Nutrient balances in particular are highly dynamic and sensitive to interannual variability in climate and crop management, making point-in-time estimates potentially misleading as representations of longer-term trends.

Fourth, the micronutrient dimension of the Bundelkhand nutrient balance is especially poorly documented in the peer-reviewed literature, and this review's treatment of secondary and micronutrients is accordingly less comprehensive than its discussion of macronutrients. Future research should prioritise systematic assessment of micronutrient balances across the full range of soils and cropping systems in the region.

Fifth, the review does not model or quantify the economic dimensions of nutrient balance deficits, nor does it provide detailed cost–benefit analyses of the integrated nutrient management strategies recommended. Such economic analyses, whilst beyond the scope of the present review, would be a valuable complement to the agronomic and ecological assessment provided here and would strengthen the case for policy investment in soil fertility restoration in Bundelkhand.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Bhattacharyya, R., Kundu, S., Prakash, V., & Gupta, H. S. (2008). Sustainability under combined application of mineral and organic fertilizers in a rainfed soybean–wheat system of the Indian Himalayas. *European Journal of Agronomy*, 28(1), 33–46. https://doi.org/10.1016/j.eja.2007.04.006

Bindraban, P. S., Dimkpa, C., Nagarajan, L., Roy, A., & Rabbinge, R. (2015). Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. *Biology and Fertility of Soils*, 51(8), 897–911. https://doi.org/10.1007/s00374-015-1039-7

Chivenge, P., Vanlauwe, B., & Six, J. (2011). Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant and Soil*, 342(1–2), 1–30. https://doi.org/10.1007/s11104-010-0626-5

FAO & ITPS. (2015). *Status of the world's soil resources (SWSR) – Main report*. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils. http://www.fao.org/3/a-i5199e.pdf

FAO. (2004). *Scaling soil nutrient balances: Enabling mesolevel applications for African realities*. FAO Fertilizer and Plant Nutrition Bulletin No. 15. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/y5622e/y5622e00.htm

Gruber, N., & Galloway, J. N. (2008). An Earth-system perspective of the global nitrogen cycle. *Nature*, 451(7176), 293–296. https://doi.org/10.1038/nature06592

Khambalkar, P. A., Agrawal, S., Dhaliwal, S. S., Yadav, S. S., Sadawarti, M. J., Singh, A., ... & Afreen, N. (2025). Sustainable nutrient management balancing soil health and food security for future generations. *Applied Food Research*, 5(2), 101087.

Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. *Food Security*, 1(1), 45–57. https://doi.org/10.1007/s12571-009-0009-z

Malo, S. K., & Saha, S. (2025). Assessment of the soil fertility index (SFI) for sustainable nutrient management in rice-based cropping systems of Barind tract of West Bengal, India. *Discover Soil*, 2, 96. https://doi.org/10.1007/s44378-025-00130-8

Meena, V. S., Meena, S. K., Verma, J. P., Kumar, A., Aeron, A., Mishra, P. K., Bisht, J. K., Pattanayak, A., Naveed, M., & Dotaniya, M. L. (2017). Plant beneficial rhizospheric microorganism (PBRM) strategies to improve nutrients use efficiency: A review. *Ecological Engineering*, 107, 8–32. https://doi.org/10.1016/j.ecoleng.2017.06.058

Pathak, H., Mohanty, S., Jain, N., & Bhatia, A. (2010). Nitrogen, phosphorus, and potassium budgets in Indian agriculture. *Nutrient Cycling in Agroecosystems*, 86(3), 287–299. https://doi.org/10.1007/s10705-009-9292-5

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., & Gerten, D. (2009). Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research*, 45(7), W00A12. https://doi.org/10.1029/2007WR006767

Roy, R. N., Misra, R. V., Lesschen, J. P., & Smaling, E. M. A. (2003). *Assessment of soil nutrient balance: Approaches and methodology*. FAO Fertilizer and Plant Nutrition Bulletin No. 14. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/Y4611E/y4611e00.htm

Sattari, S. Z., Bouwman, A. F., Giller, K. E., & van Ittersum, M. K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Sciences*, 109(16), 6348–6353. https://doi.org/10.1073/pnas.1113675109

Sharda, V. N., Dogra, P., & Prakash, C. (2010). Assessment of production losses due to water erosion in rainfed areas of India. *Journal of Soil and Water Conservation*, 65(2), 79–91. https://doi.org/10.2489/jswc.65.2.79

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241(2), 155–176. https://doi.org/10.1023/A:1016125726789

Smaling, E. M. A., & Fresco, L. O. (1993). A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). *Geoderma*, 60(1–4), 235–256. https://doi.org/10.1016/0016-7061(93)90029-K

Sobhy, D. M., & Anandhi, A. (2025). Soil nutrient monitoring technologies for sustainable agriculture: A systematic review. *Sustainability*, 17(18), 8477. https://doi.org/10.3390/su17188477

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A. K., & Kundu, S. (2013). Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity and sequestering carbon. *Advances in Agronomy*, 121, 253–329. https://doi.org/10.1016/B978-0-12-407685-3.00005-0

Srinivasarao, Ch., Vittal, K. P. R., Venkateswarlu, B., Wani, S. P., Sahrawat, K. L., Marimuthu, S., & Kundu, S. (2009). Carbon stocks in different soil types under diverse rainfed production systems in tropical India. *Communications in Soil Science and Plant Analysis*, 40(15–16), 2338–2356. https://doi.org/10.1080/00103620903111277

Stewart, W. M., Dibb, D. W., Johnston, A. E., & Smyth, T. J. (2005). The contribution of commercial fertilizer nutrients to food production. *Agronomy Journal*, 97(1), 1–6. https://doi.org/10.2134/agronj2005.0001

Timsina, J. (2018). Can organic sources of nutrients increase crop yields to meet global food demand? *Agronomy*, 8(10), 214. https://doi.org/10.3390/agronomy8100214

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L., & Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, 39(1), 17–24. https://doi.org/10.5367/000000010791169998

Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A., Nziguheba, G., Ojima, D., Palm, C. A., Robertson, G. P., Sanchez, P. A., Townsend, A. R., & Zhang, F. S. (2009). Nutrient imbalances in agricultural development. *Science*, 324(5934), 1519–1520. https://doi.org/10.1126/science.1170261

Wani, S. P., Pathak, P., Jangawad, L. S., Eswaran, H., & Singh, P. (2003). Improved management of Vertisols in the semiarid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management*, 19(3), 217–222. https://doi.org/10.1079/SUM2003196

World Bank. (2008). *World development report 2008: Agriculture for development*. The World Bank. https://doi.org/10.1596/978-0-8213-6807-7

Zörb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture – Status and perspectives. *Journal of Plant Physiology*, 171(9), 656–669. https://doi.org/10.1016/j.jplph.2013.08.008

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/153491