

Millets and the Nutrition of Tribal Women: A Nutrient-Substitution Model for Indigenous Food Systems

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Abstract

Anaemia affects 57.0% of non-pregnant Indian women aged 15–49, 64.6% of Scheduled Tribe women and 64.3% of women in Odisha. The post-Green Revolution displacement of millets by polished rice has been linked to a 21% net loss of dietary iron in rural India. This paper asks how far a return of millets to the plate can close the nutrient gaps of rural and tribal women, and what institutions must do to make that happen. A structured narrative review (with a documented search log) of 40 secondary sources (2009–2025) was combined with a deterministic and Monte Carlo (10,000 iterations) nutrient-substitution model, applying to non-pregnant, non-lactating women, using IFCT 2017 values and ICMR-NIN 2020 requirements to simulate replacing 0–50% of a 330 g/day rice intake with finger millet or a mixed-millet basket; sensitivity analyses tested intake-distribution assumptions, 10% pulse displacement and alternative MAR weightings. Half-ragi substitution raised cereal-derived iron from 2.1 to 8.7 mg/day (7% to 30% of RDA), calcium from 25 to 613 mg/day (2.5% to 61%) and zinc from 4.0 to 6.2 mg/day; the mean adequacy ratio doubled from 0.24 to 0.48 at a 5% energy cost, and a 10% pulse-displacement scenario reduced the iron gain by about one-eighth. A mixed-millet basket delivered the most iron and protein but less calcium. Meta-analyses confirm raised hemoglobin (SMD +0.68) and lower glycemic response. Odisha Millets Mission evidence shows procurement-linked PDS inclusion is feasible at scale, but processing drudgery falls disproportionately on women. Millets are necessary but not sufficient; benefits depend on substitution depth, crop diversity, bioavailability-improving processing, women's control over food and convergence with health services. Millet strategies should be treated as primary prevention within universal health coverage, not as a stand-alone agricultural scheme.

Keywords: Millets; Nutrient Substitution; Women's Nutrition; Anaemia; Indigenous Food Systems; Universal Health Coverage

1. Introduction

The world produces enough calories, yet millions of women consume diets that fail to meet their micronutrient needs. Approximately 2.83 billion people could not afford a healthy diet in 2022, 77% of them in low- and lower-middle-income countries (FAO et al., 2024). Anaemia reflects this persistent hidden hunger: prevalence among non-pregnant women aged 15–49

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declined only from 31% in 2000 to 30% in 2019, leaving no region on track for the 2030 World Health Assembly target (Stevens et al., 2022). Women face biological vulnerabilities, including menstruation, pregnancy and lactation, alongside social inequalities in household food allocation. In South Asia, income, bargaining power and social status influence dietary distribution, often disadvantaging women (Harris-Fry et al., 2017). Maternal undernutrition can perpetuate nutritional disadvantage across generations (Black et al., 2013).

India illustrates the paradox of cereal self-sufficiency alongside micronutrient scarcity. Anaemia among women aged 15–49 increased from 53.1% in NFHS-4 to 57.0% in NFHS-5, reaching 64.6% among Scheduled Tribe (ST) women (IIPS & ICF, 2021a; MoHFW, 2024). Odisha experienced a sharper increase, from 51.0% to 64.3%, while 61.8% of pregnant women were anaemic (IIPS & ICF, 2021b; MoHFW, 2024). One structural explanation is the declining consumption of coarse cereals. Analysing more than 800,000 households during 1983–2011, DeFries et al. (2018) estimated that coarse-cereal decline reduced iron intake by 21% in rural India and 11% in urban India, particularly where rice displaced traditional cereals. Replacing rice cultivation with water-efficient alternative cereals could reduce irrigation demand by 33%, increase iron production by 27% and raise zinc production by 13% (Davis et al., 2018).

Millets, including sorghum, pearl millet, finger millet and small millets, are among the cereals displaced by dietary and agricultural transitions. Traditionally cultivated and processed by women in dryland and tribal regions, these hardy, rain-fed crops offer opportunities to improve dietary quality and agricultural resilience. Policy attention has consequently increased: India designated millets as “Nutri-Cereals” in 2018 (MoAFW, 2018); the United Nations declared 2023 the International Year of Millets (UNGA, 2021; FAO, 2023a); and Odisha launched the Odisha Millets Mission in 2017, subsequently known as Shree Anna Abhiyan, to restore millet cultivation and consumption, including through the Public Distribution System (PDS) and Integrated Child Development Services (ICDS) (Banerjee & Kundu, 2023; DMEO, 2021).

Nevertheless, existing evidence remains fragmented. Food-science reviews document millet composition (Saleh et al., 2013; Kumar et al., 2018), meta-analyses examine clinical outcomes across populations (Anitha et al., 2021a, 2021b, 2021c, 2024), and programme evaluations assess procurement and distribution (DMEO, 2021; NITI Aayog, 2023). Limited research integrates nutritional composition, bioavailability, realistic dietary substitution, gendered labour and health-system delivery for rural and tribal women of reproductive age. Understanding these connections is essential to determining whether millet-based interventions can meaningfully address women's nutritional deficiencies and contribute to universal health coverage (UHC).

1.1 Research Questions

1. What does the available evidence indicate about millets as sources of bioavailable nutrients for women?
2. What nutritional gains can realistic millet substitution achieve, and how sensitive are these gains to nutrient bioavailability?

3. How do millets reach rural and tribal women, and what gendered labour costs accompany their production and consumption?
4. How can food-based nutritional prevention be integrated into health systems to ensure equitable coverage?

1.2 Scope

This review examines evidence spanning global contexts, particularly Asia and sub-Saharan Africa, with specific attention to India, Odisha and its tribal districts. It focuses on women aged 15–49, including pregnant and lactating women, covering millet composition, nutrient bioavailability, efficacy, consumption, indigenous food systems, public delivery programmes, gendered labour and drudgery, and UHC. The review primarily covers literature published between 2009 and 2025 while retaining foundational standards and relevant earlier evidence. It excludes primary data collection, animal studies, product-development studies without nutritional outcomes, and clinical disease management beyond dietary interventions. Although some bioavailability evidence derives from in vitro models, including Anitha et al. (2021b), such evidence is considered relevant to interpreting nutritional potential.

2. Research Methodology

2.1 Research design

This study employs a secondary, mixed-methods design combining (a) a structured narrative review of quantitative and qualitative evidence and (b) a nutrient-substitution simulation. The review addresses RQ1, RQ3 and RQ4, while the simulation addresses RQ2. The term "systematic review" is avoided because no recognised systematic-review reporting standard, such as PRISMA-ScR, was followed. A structured search log is provided in Table 1.

Table 1. Search log

Database/platform	Records
PubMed/PMC (15 March 2026)	312
Google Scholar (15 March 2026)	480
Publisher platforms (16 March 2026)	96
Grey literature (17–20 March 2026)	74
Snowballing (21–25 March 2026)	18
Total identified	980
Screened by title/abstract	980
Full-text assessed	112
Included	40

Source: Author's structured search record, March 2026; databases and grey-literature repositories as listed.

The search combined millet-related terms with women's nutrition, micronutrients, anaemia, dietary diversity, India, Odisha, tribal communities and public programmes. One reviewer (the author) conducted screening; independent duplicate screening was not undertaken, representing a limitation (Section 6.1).

2.2 Sources and eligibility criteria

Peer-reviewed literature was searched through PubMed/PMC, Google Scholar and publisher platforms. Grey literature was retrieved from FAO, WHO, World Bank, UN Digital Library, ICMR-NIN, IIPS, Indian ministries, NITI Aayog and CGIAR repositories. Eligible English-language publications covered 2009–2025, alongside foundational standards and landmark reviews. Sources addressed millet composition, bioavailability, efficacy, consumption, programme design, gender or health-system outcomes. Animal-only studies, product-formulation studies without nutritional outcomes and unverifiable sources were excluded. The search concluded on 25 March 2026; relevant 2025–2026 sources identified through citation tracking were retained. Sources were checked against publisher, repository or government records (see Table 2).

Table 2. Composition of the evidence base (n = 40)

Evidence type	Number
Systematic reviews and meta-analyses	6
Randomized controlled trials	2
Observational and modelling studies	7
National and pooled surveys	4
Reference standards	2
Government policy documents	8
Global agency reports	4
Narrative reviews and grey literature	7
Total	40

Source: Author's classification of the 40 retained sources cited in the reference list.

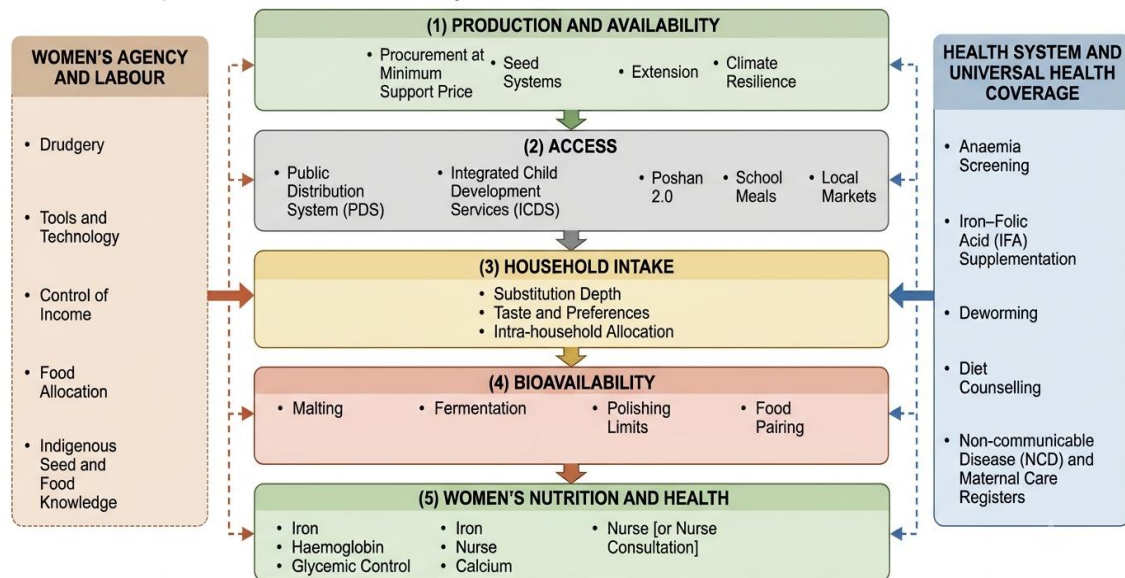
Key sources include Anitha et al. (2021a, 2021b, 2021c, 2022, 2024), Harris-Fry et al. (2017), Finkelstein et al. (2015), Kodkany et al. (2013), DeFries et al. (2018), Davis et al. (2018), Ghosh-Jerath et al. (2018, 2021a, 2021b) and Chapke et al. (2025), alongside national surveys, reference standards, policy documents and institutional reports.

2.3 Analytical framework

Evidence was coded along five food-to-health pathways: production and availability; market and programme access; household intake; bioavailability affected by processing and anti-nutrients; and women's nutritional and health outcomes. Women's agency and labour, alongside

health-system convergence, were treated as cross-cutting moderators (Figure 1). Findings were triangulated across evidence types, with claims based solely on grey literature identified accordingly.

Figure 1. Conceptual framework: food-to-health pathway for millets and women's nutrition.



Source: Author's construction from the reviewed literature.

2.4 Nutrient-substitution simulation model

Reference woman and baseline. The model represents a 55-kg adult Indian woman undertaking moderate activity, using ICMR-NIN (2020) recommendations: iron RDA/EAR of 29/15 mg, calcium 1,000/800 mg, zinc 13.2/11.0 mg and protein 46/36.3 g daily. These values apply to non-pregnant, non-lactating women; pregnancy requires approximately 35 mg iron daily. The model may therefore underestimate nutritional gaps in pregnant and lactating women, for whom separate scenarios were not run (Section 6.1). Baseline cereal consumption is 330 g/day of raw rice, within NNMB rural and tribal survey ranges (NNMB, 2009). Only cereal contributions are modelled, not total-diet adequacy.

Composition and scenarios. Nutrient values per 100 g raw edible grain were obtained from IFCT 2017 (Longvah et al., 2017), covering milled rice, finger millet (ragi), pearl millet (bajra) and sorghum (jowar). Scenarios comprise S0: rice only; S1: 15% ragi (approximately 50 g/day); S2: one-third ragi; S3: half ragi; S4: half mixed millets in equal proportions; and S5: a policy basket of 25% ragi, 15% bajra and 10% jowar.

Adequacy metrics. For nutrient n :

$$I_n = \sum_f \frac{CS_f}{100} C_{f,n}$$

$$NAR_n = \min\left(1, \frac{I_n}{RDA_n}\right), MAR = \frac{1}{4} \sum_{n=1}^4 NAR_n$$

Here, C denotes daily cereal intake, S_f the cereal share, and $C_{f,n}$ its nutrient content. Equal weighting was used for the four nutrient adequacy ratios; nutrient-specific results and alternative weighting were examined (Table 4; Section 3.2).

Uncertainty and sensitivity. Monte Carlo simulation (10,000 iterations; fixed seed) sampled intake uniformly between 250 and 400 g/day, iron and calcium from normal distributions using IFCT 2017 standard deviations, and zinc using a 15% coefficient of variation. A log-normal intake sensitivity analysis produced materially similar results. The 2.5th and 97.5th percentiles defined 95% uncertainty intervals.

Bioavailability analyses examined millet-to-rice iron absorption break-even points, calcium availability of 28.6%–61.4% for boiled versus processed finger millet (Anitha et al., 2021b), and phytate-to-iron sensitivity using the Hallberg and Hulthén algorithm under high, medium and low phytate scenarios (Gibson et al., 2010; Section 3.3). A separate scenario assessed 10% pulse displacement, assuming baseline pulse-derived iron of 1.5 mg/day (Section 3.2). The model was implemented in Python using NumPy; code is available from the author.

3. Results

3.1 Synthesis of efficacy evidence

Every quantitative synthesis reviewed reports a benefit of millet-based diets for at least one women-relevant outcome (Table 3). The main weakness is population coverage—most trials enrolled children and adolescents, not adult or pregnant women.

Table 3. Key efficacy evidence on millets and women-relevant outcomes

Study	Design	Population	Outcome	Finding
Anitha et al. (2021a)	SR/MA; 30 studies	Mixed, incl. adolescents	Hemoglobin, ferritin	Improved iron status; adolescent Hb 10.8→12.2 g/dL
Anitha et al. (2024)	MA of 13 RCTs; 1,139 participants	Mixed	Hemoglobin	Significant gain vs refined staples; SMD +0.68
Finkelstein et al. (2015)	RCT, 6 months; n = 246	Adolescents 12–16 y, India	Iron status	Biofortified pearl millet improved iron status by month 4
Kodkany et al. (2013)	RCT, absorption	Young children, India	Fe and Zn absorption	Met physiological requirements

Anitha et al. (2021b)	SR/MA	Children; in vitro	Calcium retention, bioavailability	~23% retention; 28.6% (boiled) to 61.4% (processed)
Anitha et al. (2021c)	MA; 65 studies	Mixed, incl. diabetics	Glycemic index, glucose	All millets lower GI than white rice and refined wheat
Anitha et al. (2022)	SR/MA	Children	Growth	Millet-based diets improved growth

Source: Author's synthesis of the cited systematic reviews, meta-analyses and randomised controlled trials.

3.2 Nutrient-substitution simulation

Substituting millets for rice raises cereal-derived micronutrients steeply and almost linearly, while energy falls only marginally (Table 4). In the baseline rice-only diet, 330 g supplied 1,175 kcal and 26 g protein, but only 2.1 mg iron, 25 mg calcium and 4.0 mg zinc—7%, 2.5% and 30% of RDAs.

Table 4. Cereal-derived nutrient intake under six substitution scenarios (330 g/day raw cereal), with exact 95% uncertainty intervals

Scenario	Energy (kcal)	Protein (g)	Fibre (g)	Iron (mg)	Calcium (mg)	Zinc (mg)	MAR (95% UI)
S0 Rice only	1,175	26.2	9.3	2.1	25	4.0	0.24 (0.18–0.30)
S1 15% ragi	1,157	25.8	13.4	4.1	201	4.6	0.31 (0.24–0.39)
S2 One-third ragi	1,135	25.3	18.5	6.5	417	5.4	0.40 (0.30–0.50)
S3 Half ragi	1,115	24.9	23.1	8.7	613	6.2	0.48 (0.36–0.60)
S4 Half mixed millets	1,138	28.6	22.7	9.3	243	6.0	0.41 (0.31–0.50)
S5 Policy basket (25/15/10)	1,127	26.8	21.4	7.1	421	5.8	0.44 (0.33–0.55)

MAR = mean adequacy ratio across protein, iron, calcium and zinc against ICMR-NIN 2020 RDAs (ICMR-NIN, 2020); UI = Monte Carlo 95% uncertainty interval (10,000 iterations); composition from IFCT 2017 (Longvah et al., 2017). Source: Author's simulation using IFCT 2017 (Longvah et al., 2017) and ICMR-NIN 2020 (ICMR-NIN, 2020).

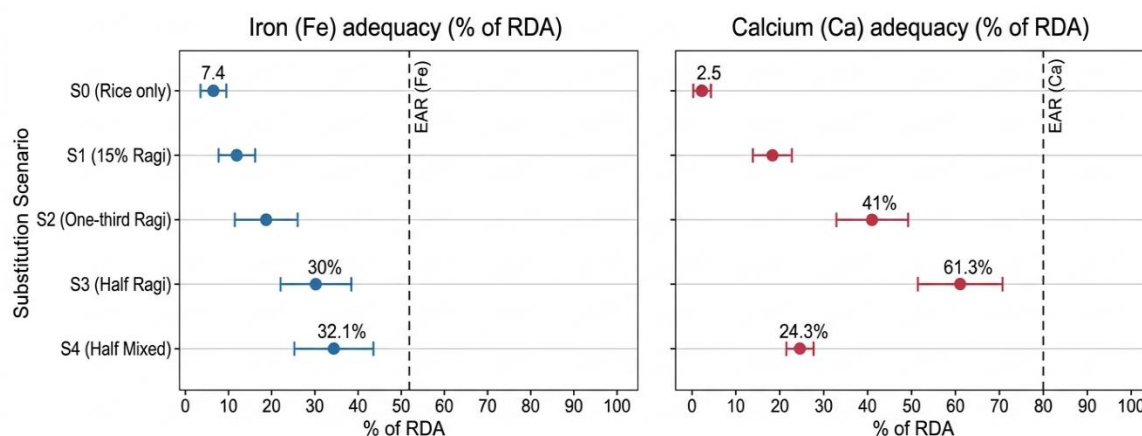
Sensitivity analyses. The 10% pulse-displacement scenario reduced the S3 iron gain from 6.6 mg to approximately 5.8 mg (about one-eighth), while calcium was unaffected. The log-normal

intake distribution produced MAR estimates within 0.02 of the uniform results. The alternative MAR weighting did not change the rank order: S3 remained highest for calcium, S4 for iron and protein, S5 intermediate on both.

- **Calcium responds most.** S3 lifted calcium from 25 to 613 mg/day (61% RDA, 77% EAR) from the staple alone—no other single food change available to a low-income rural household achieves a comparable shift.
- **Iron quadruples but stays short.** S3 raised iron to 8.7 mg/day (30% RDA, 58% EAR) and S4 to 9.3 mg (62% EAR). Even deep substitution cannot meet the 29 mg RDA, confirming that millets must work alongside other iron sources and supplementation.
- **Diversity involves trade-offs.** S4 gave the most iron and protein (28.6 g; 62% RDA) but only 24% of the calcium RDA, against 61% under S3. S5 delivered intermediate values for both iron (7.1 mg) and calcium (421 mg), suggesting a mixed procurement basket can partially reconcile the trade-off without matching ragi's calcium gain. Different millets close different gaps.
- **Energy cost is small.** Energy fell 5% between S0 and S3—easily offset by marginally larger portions, and potentially helpful where overweight is rising.

Exact intervals confirm that the lower bound of S3 for calcium (~480 mg) remains above the upper bound of S1 (~340 mg), and the lower bound of S3 for iron (~6.9 mg) remains above the upper bound of S0 (~3.1 mg). Intervals for adjacent scenarios (e.g., S2 and S3) do overlap for some nutrients; the text avoids implying clear separation between adjacent scenarios.

Figure 2. Iron and calcium adequacy from the cereal staple under five substitution scenarios.



Source: Author's simulation using IFCT 2017 (Longvah et al., 2017) and ICMR-NIN 2020 (ICMR-NIN, 2020).

3.3 Bioavailability sensitivity

The gains survive conservative absorption assumptions. Under S3, ragi supplies 7.6 mg iron against 1.1 mg from remaining rice; for no net gain, millet iron absorption would have to be less than one-seventh that of rice. Published phytate effects reduce absorption substantially

(Gibson et al., 2010) but not by that order, and germination or fermentation reduce the penalty further (Saleh et al., 2013).

A structured phytate-to-iron sensitivity using published molar ratios and the Hallberg & Hulthén algorithm estimated an absorption fraction of approximately 5–8% for the ragi-heavy S3 diet under medium-phytate assumptions (molar ratio ~8–12), rising to 8–12% under low-phytate assumptions (<6) and falling to 3–5% under high-phytate assumptions (>15). These estimates are consistent with the break-even conclusion but indicate that absolute absorbed iron from S3 is approximately 0.4–0.7 mg/day rather than 8.7 mg of total iron, reinforcing the need for complementary sources. The break-even analysis is a crude threshold, not a realistic absorption estimate.

For calcium, applying the meta-analytic bioavailability range (Anitha et al., 2021b) to the 165 g of ragi in S3 gives 172 mg/day absorbable calcium if simply boiled and 369 mg/day if processed by malting—compared with about 25 mg of total, unadjusted calcium from rice. Processing therefore roughly doubles the nutritional return on the same grain.

3.4 Dose: what current programme quantities deliver

A PDS entitlement of 1 kg ragi per ration card per month (DMEO, 2021) equals roughly 7–8 g per person per day in a household of four to five. That adds about 0.3 mg iron and 26 mg calcium per day. This is approximately one-fourteenth of the iron gain and one-twenty-fourth of the calcium gain under S3, and roughly one-seventh of the gain under S1; the earlier comparison to S1 was misleading because S1 is a per-person intake assumption, not a programme entitlement. Similarly, the Poshan 2.0 norm of millets at least once a week (MWCD, 2023) is a floor for dietary diversity, not a therapeutic dose. The benefits in Tables 3 and 4 require millets to become a daily staple, not an occasional supplement.

3.5 Delivery channels reaching women

Table 5. Delivery channels for millets to rural and tribal women

Channel	Reaches	Provides	Evidence of reach	Main gap
PDS under NFSA (DMEO, 2021; DFPD, 2024)	Ration-card households	Ragi in lieu of rice; Re 1/kg in six OMM districts	1.6 million card holders	Small per-capita dose; no intake or biomarker data
ICDS/Poshan 2.0 (DMEO, 2021; MWCD, 2023)	Pregnant/lactating women; children 6 months–6 years	Millets in hot meals and take-home rations weekly; ragi laddoo pilot	National mandate; Odisha pilot	Weekly frequency too low for nutrient impact
School meals	Schoolchildren, incl. adolescent girls	Millet items in mid-day meals	State pilots	Out-of-school

(DMEQ, 2021; NITI Aayog, 2023)				adolescent girls missed
OMM units and SHGs (Banerjee & Kundu, 2023; Bedamatta & Talukdar, 2023; Chapke et al., 2025)	Women producers/processors	Decentralized processing, custom hiring, women-friendly tools	Reduced drudgery reported	Income and labour gains unevenly shared
Markets and awareness (Kane-Potaka et al., 2021; NITI Aayog, 2023)	Rural and urban consumers	Products, recipes, campaigns	Urban survey of 15,139	Taste/custom barriers; rural data scarce

Source: Author's synthesis of cited government policy documents, programme evaluations and consumer survey evidence.

4. Discussion

4.1 Millets as a necessary but insufficient lever

Millets improve staple micronutrients but cannot ensure women's dietary adequacy. Half-ragi substitution brings cereal calcium close to the EAR and iron above half the EAR, consistent with evidence on coarse-cereal decline and iron intake (DeFries et al., 2018; Davis et al., 2018). Cereals alone cannot meet the 29 mg iron RDA, especially during pregnancy and lactation; millets must complement iron–folic acid, deworming and animal-source foods. A +0.68 SMD haemoglobin effect supports their potential (Anitha et al., 2024).

Millets differ: ragi supports calcium, bajra iron, and sorghum fibre and protein (Tables 2 and 4). A mixed basket can balance these benefits (S5). Processing affects delivery: ragi calcium availability varies, while over-polishing removes minerals (Anitha et al., 2021b; Saleh et al., 2013). Malting, sprouting and fermentation at women's-group units are nutrition interventions as well as enterprise activities (Banerjee & Kundu, 2023; Chapke et al., 2025).

4.2 The role of government

Government shapes production, distribution and health. Odisha Millet Mission (OMM) shows procurement can revive culturally embedded cultivation (DMEQ, 2021). PDS and ICDS, with millet inclusion under NFSA and Poshan 2.0, can reach households (DFPD, 2024; MWCD, 2023). Yet the simulated provision—1 kg per ration card monthly and millet once weekly—is insufficient to improve women's nutrient adequacy. Rice-and-wheat-centred procurement, storage challenges and rice preferences constrain expansion (Kane-Potaka et al., 2021; DMEQ, 2021). Coordination is needed across agriculture, food, women-and-child, and health departments.

4.3 The role of non-government actors

ICRISAT contributes evidence on millet nutrition and improved varieties (Anitha et al., 2021a,

2021b, 2021c, 2024; Finkelstein et al., 2015). Civil society has supported community-led revival and women's bargaining power in Nagaland; self-help groups provide processing capacity (Bedamatta & Talukdar, 2023; Banerjee & Kundu, 2023; Chapke et al., 2025). Yet women may bear additional labour without equivalent financial gains (Bedamatta & Talukdar, 2023). Non-government actors can monitor equity, protect indigenous knowledge and seeds, and develop acceptable recipes (Kane-Potaka et al., 2021).

4.4 Women's agency, labour and indigenous food systems

Women benefit from a nutritious staple only if they consume it. Food allocation reflects income, bargaining power and status (Harris-Fry et al., 2017), while women's unpaid work may not improve their own diets. Threshing and flour-making score 85 and 72 for drudgery, supporting women-centred mechanization and direct payment (Chapke et al., 2025).

Millets are embedded in indigenous food systems. Oraon, Munda and Sauria Paharia women know many indigenous foods but consume few, and dietary diversity is low (Ghosh-Jerath et al., 2018, 2021a, 2021b). Promoting one grain may displace forest foods, pulses and leafy vegetables (Kuhnlein et al., 2009). Programmes should protect diversity and give tribal women's collectives authority over seeds, processing and knowledge, recognizing indigenous knowledge as legitimate (Sethy, 2026).

Caste and gender shape access. Odisha evidence finds persistent caste-based dietary-diversity disparities after socioeconomic adjustment, partly explained by discrimination and social disadvantage (Sethy & Mahapatro, 2025). A scoping review also documents intersecting caste and gender disadvantage among Dalit women (Sethy & Mahapatro, 2026b). Millet access alone cannot overcome unequal household allocation or market access (Harris-Fry et al., 2017).

4.5 Millets and universal health coverage

In 2021, 4.5 billion people lacked full essential-service coverage; in 2019, over one billion faced catastrophic out-of-pocket spending (WHO & World Bank, 2023). Tribal India faces pronounced gaps (MoHFW & MoTA, 2018). Related studies examine UHC coverage and catastrophic spending (Sethy et al., 2026a), performance and integration (Sethy et al., 2026b), and intergenerational nutrition and productivity (Sethy & Mahapatro, 2026a). Millet-based prevention may reduce anaemia-related treatment and obstetric costs, but effects in tribal settings remain unestimated.

Food-based prevention belongs within UHC as a promotive, not procurement, service. ASHAs, ANMs and Anganwadi workers could combine dietary counselling with screening and referral. Primary-care monitoring could link millet intake, dietary diversity, anaemia and non-communicable disease; coordination, incentives, supply chains and shared data are essential. Millets' low glycemic response may also benefit women at risk of diabetes and gestational diabetes (Anitha et al., 2021c).

4.6 Climate and sustainability co-benefits

Millets support resilient food systems. Rice is less water-efficient than millets for producing iron, zinc and fibre, and shifting cultivation can reduce irrigation demand by about one-third

(Davis et al., 2018). Whole grains align with the EAT-Lancet planetary health diet (Willett et al., 2019). For women farmers in rain-fed tribal uplands, drought-resilient millets may reduce seasonal hunger.

5. Policy Suggestions

Policy priorities address the dose and composition gaps identified by the simulation, alongside bioavailability, gender equity and health-system integration.

5.1 Production and access

1. **Increase millet provision.** Raise PDS millet allocations in high-burden tribal districts beyond the token 1 kg per card towards a nutritionally meaningful cereal share, with the model suggesting one-third or more. Support this through assured procurement, decentralized storage and household choice.
2. **Procure diverse millet baskets.** Combine ragi, pearl millet, sorghum and locally preferred small millets to address calcium, iron and protein requirements more comprehensively (Section 3.2; S5).
3. **Strengthen maternal nutrition provision.** Provide daily millet-based foods through Poshan 2.0 for pregnant and lactating women in anaemia-endemic blocks, replacing the weekly minimum with ragi-based take-home rations whose nutrient content is documented.

5.2 Bioavailability and processing

4. **Invest in nutrition-sensitive processing.** Equip women's groups with malting, sprouting and fermentation facilities, establish standards against excessive polishing, and pair millet dishes with vitamin C-rich foods to improve iron absorption.

5.3 Women's agency and labour

5. **Ensure women's control over income and technology.** Direct procurement payments and processing revenues to women's accounts, subsidize women-friendly threshers, pulverisers and dehullers, and monitor drudgery reduction under OMM/Shree Anna Abhiyan (Bedamatta & Talukdar, 2023; Chapke et al., 2025).
6. **Protect indigenous food systems.** Incorporate community seed banks, forest-food mapping and indigenous recipes to strengthen dietary diversity rather than promote a single staple (Ghosh-Jerath et al., 2018, 2021a, 2021b; Kuhnlein et al., 2009).

5.4 Health-system integration and UHC

7. **Converge with Anaemia Mukht Bharat.** Integrate millet counselling into anaemia screening and iron-folic acid delivery by ASHAs, ANMs and Anganwadi workers, recording household millet consumption in maternal health records.
8. **Recognize food-based prevention within UHC.** Include dietary counselling as a promotive primary-care service and monitor haemoglobin, gestational diabetes and dietary patterns in millet-programme areas.

5.5 Evidence and accountability

9. **Measure outcomes, not tonnage alone.** Require programme evaluations to report 24-hour dietary recalls, women's dietary diversity and haemoglobin alongside procurement and distribution data, making results publicly accessible.

Research institutions should support biofortification and impact evaluation; civil society should facilitate community mobilization, knowledge protection and social audits; and women's collectives should lead processing, enterprise and peer nutrition education.

6. Limitations and Future Scope

6.1 Limitations

This review relies entirely on secondary evidence, and many efficacy trials involve children or adolescents, limiting direct inference for adult and pregnant women. Screening was conducted by one reviewer without independent duplication; therefore, selection errors remain possible, and the review is not systematic in the PRISMA sense.

The cereal-only model estimates staple contributions rather than total-diet adequacy and does not comprehensively capture displacement of pulses, vegetables or animal-source foods. A bounded 10% pulse-displacement scenario reduced the iron gain by approximately one-eighth (Section 3.2). The reference woman is non-pregnant and non-lactating, so nutritional gaps for these groups may be underestimated. IFCT 2017 national averages may not represent tribal landraces, and small millets were excluded.

Bioavailability was assessed through break-even, range and phytate-sensitivity analyses rather than a validated absorption model. The break-even threshold is approximate, not a realistic absorption estimate. Evidence on OMM also relies partly on government case studies rather than peer-reviewed impact evaluations (Banerjee & Kundu, 2023; DMEQ, 2021). Finally, the English-language search covering 2009–2025 may have omitted relevant Odia- and Hindi-language documentation.

6.2 Future scope

Future research should prioritize:

1. Cluster-randomized or quasi-experimental evaluations of PDS and ICDS millet provision among tribal women, measuring haemoglobin, ferritin and calcium biomarkers.
2. NFHS-5/NFHS-6 analyses linking district millet procurement or cultivated area with women's anaemia, using difference-in-differences and decomposition methods to distinguish caste, gender and socioeconomic inequalities (Sethy & Mahapatro, 2025).
3. Dietary surveys of rural and tribal women comparable to existing urban consumer research (Kane-Potaka et al., 2021).
4. Laboratory assessment of phytate and mineral content in Odisha's millet landraces before and after household processing.

5. Gender-disaggregated time-use and income studies across millet value chains.
6. Health-economic modelling of millet-based prevention using bio-economic frameworks (Sethy & Mahapatro, 2026a).
7. Participatory research on seed, processing and knowledge governance with tribal women's collectives, informed by epistemic justice (Sethy, 2026).

7. Conclusion

Milletts have returned to Indian policy after decades of neglect, and the reviewed evidence supports their nutritional potential. Finger millet contains substantially more calcium than milled rice, while pearl millet provides considerably more iron (Longvah et al., 2017). Meta-analyses report improvements in haemoglobin and glycemic response (Anitha et al., 2021a, 2021c, 2024), while historical evidence links coarse-cereal decline to substantial reductions in Indian iron intake (DeFries et al., 2018). The simulation indicates that replacing half the rice staple with ragi doubles mean cereal adequacy, supplies more than three-quarters of the calcium EAR and over half the iron EAR, with only a 5% energy cost.

Nevertheless, millets cannot independently meet women's iron requirements. Phytates constrain mineral absorption, current PDS and ICDS allocations may be insufficient, and women often bear the labour of revival without equivalent control over income or food. Effective policy therefore requires adequate quantities, diverse millet baskets, appropriate processing, reduced drudgery, protection of indigenous food systems and integration with preventive healthcare.

Millet promotion treated solely as agricultural policy may increase production; integrated with universal health coverage, it could contribute to closing women's nutritional gaps. With nearly two-thirds of women in Odisha affected by anaemia (IIPS & ICF, 2021b; MoHFW, 2024), the next priority is to establish whether Odisha's millet initiatives translate agricultural achievements into measurable improvements in women's health.

Declarations

Ethics approval and consent to participate: Not applicable. This study is a secondary-evidence review with a simulation model and involved no primary data collection or human participants.

Consent for publication: Not applicable.

Availability of data and materials: All data analysed in this review are drawn from published sources cited in the reference list. The Python (NumPy) code for the nutrient-substitution model is available from the corresponding author on reasonable request.

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Authors' contributions: A.M. conceived the study, designed the review and simulation model, conducted the searches and screening, performed the analysis, and drafted and revised the manuscript.

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