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Galactagogue Potential of Pearl Millet (*Pennisetum glaucum*), Finger Millet (*Eleusine coracana*), and Red Sorghum (*Sorghum bicolor*): A Comprehensive Phytochemical Review of Lactation-enhancing Mechanisms

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Abstract

Background: Hypogalactia is a clinically underacknowledged barrier to sustained exclusive breastfeeding, contributing to premature weaning and compromised neonatal outcomes. Food-based galactagogues from traditional nutritional practice across South Asia and sub-Saharan Africa, particularly Pearl Millet (*Pennisetum glaucum*), Finger Millet (*Eleusine coracana*), and Red Sorghum (*Sorghum bicolor*), represent an understudied intervention whose mechanistic relevance to lactation physiology has not been systematically reviewed. **Aim:** To consolidate and critically evaluate the phytochemical evidence for the galactagogue potential of these three cereals and to map their bioactive constituents to plausible lactation-enhancing mechanisms. **Methods:** A narrative review was conducted across PubMed/MEDLINE, Scopus, and Google Scholar (1990 onwards), prioritising Scopus-indexed original research, alongside ethnobotanical sources; thirty articles and book chapters were included. **Results:** The phytochemical evidence, while largely restricted to *in vitro* and animal-model work, supports biologically plausible galactagogue activity for constituents including ferulic acid, luteolin, 3-deoxyanthocyanins, β-sitosterol, enterolignans, and condensed tannins, acting through prolactin pathway modulation, phytoestrogenic receptor binding, mammary antioxidant defence, anti-inflammatory activity, and nutritional repletion of iron and calcium. No randomised controlled trial has investigated any of the three cereals specifically as galactagogues. **Conclusion:** Well-designed *in vitro* mechanistic studies and clinical trials with standardised millet preparations are essential to translate this phytochemical evidence into validated nutritional recommendations.

Major Findings: All three millets carry phytochemical profiles consistent with multi-pathway galactagogue activity; rigorous clinical investigation for lactation outcomes has not yet been undertaken for any of the three cereals.

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Abbreviations: CAM: Complementary and Alternative Medicine; COX-2: Cyclooxygenase-2; DPPH: 2,2-diphenyl-1-picrylhydrazyl; ER: Oestrogen Receptor; ERβ: Oestrogen Receptor Beta; GAE: Gallic Acid Equivalents; IL-1β: Interleukin-1 beta; NF-κB: Nuclear Factor Kappa-light-chain-enhancer of activated B cells; ROS: Reactive Oxygen Species; TPC: Total Phenolic Content; TNF-α: Tumour Necrosis Factor Alpha.

1. Introduction

Adequate breast milk production is widely recognised as the nutritional foundation of neonatal health, yet the physiological challenge of hypogalactia receives disproportionately limited attention within routine postpartum clinical care. The World Health Organisation has recommended exclusive breastfeeding through the first six months of life based on extensive evidence for breast milk's immunological, hormonal, and nutritional composition, which no commercial formula has replicated in full[1,2]. Despite this, global rates of exclusive breastfeeding at six months remain below 45%, with insufficient milk production cited as one of the most prevalent reasons for early cessation, a finding consistent across both high- and low-income country settings[3].

Hypogalactia, broadly defined as failure to produce milk volumes adequate to meet infant demand, affects an estimated 5–15% of postpartum women in high-income settings, with considerably higher rates documented in populations with poor nutritional status, high parity, or limited postnatal support[4]. The downstream consequences, including compromised neonatal immunity, impaired metabolic programming, and early formula introduction, are well characterised, though the clinical management of insufficient milk production remains poorly standardised. Lactation is regulated primarily through prolactin, secreted by anterior pituitary lactotrophs in response to nipple stimulation and suckling; oxytocin governs the ejection reflex[5]. Disruption of this neuroendocrine axis through stress, micronutrient deficiency, or hormonal imbalance can precipitate suboptimal output. Pharmacological galactagogues domperidone and metoclopramide most notably carry documented risks including cardiac arrhythmia and extrapyramidal side effects that substantially limit their clinical acceptability, particularly in resource-constrained settings[6].

It is within this therapeutic gap that plant-based galactagogues have attracted renewed scientific interest. Agents from fenugreek to moringa have been investigated with varying degrees of empirical support across Ayurvedic, Siddha, and African ethnomedicinal traditions[7]. Within this broader literature, millets occupy an underexplored position. Pearl Millet (*Pennisetum glaucum*), Finger Millet (*Eleusine coracana*), and Red Sorghum (*Sorghum bicolor*) are among the most widely cultivated staple cereals across sub-Saharan Africa and South Asia, precisely the regions where traditional millet consumption and breastfeeding practices most frequently co-occur within the same communities[8]. In Tamil Nadu and Karnataka, ragi (*E. coracana*) prepared as kanji, or kali, is among the most consistently recommended postpartum foods across Siddha tradition and community health practice. In Rajasthan, bajra roti with ghee features as a standard postpartum dietary recommendation. In Nigeria and Ghana, sorghum-based fermented gruel ogi, akamu, and koko are widely consumed by breastfeeding women, a practice documented across ethnobotanical surveys spanning multiple sub-Saharan communities.

What distinguishes these three cereals from most other proposed natural galactagogues is the convergence of several attributes that are rarely found together: dense micronutrient profiles, particularly iron, calcium, zinc, and magnesium, alongside repertoires of bioactive polyphenols and flavonoids with documented or plausible phytoestrogenic properties, and centuries of safe traditional use without significant adverse event reporting. Red Sorghum contains unusually high concentrations of 3-deoxyanthocyanins, a structurally distinctive polyphenol class with demonstrated antioxidant and anti-inflammatory properties potentially relevant to mammary glandular tissue integrity during peak lactation[9]. Finger Millet's polyphenol profile, dominated by condensed tannins and hydroxycinnamic acids, has demonstrated hormonal modulatory activity and oestrogenic receptor interaction in preliminary investigations[10]. Pearl Millet contributes phytosterols and lignans with structural homology to oestrogen, alongside its well-recognised

iron content directly relevant to postpartum anaemia prevention and the energetic demands of milk synthesis[11].

This review consolidates the available phytochemical and pharmacological evidence for the galactagogue potential of all three millets, examining individual bioactive constituents, mapping mechanistic pathways relevant to lactation physiology (summarised in Figure 1), and situating findings within both ethnobotanical tradition and contemporary nutritional science. The aim is to provide a rigorous scientific basis for the *in vitro* and clinical research this field requires.

2. Literature Search Strategy

A narrative review methodology was adopted, examining phytochemical evidence for the galactagogue properties of *P. glaucum*, *E. coracana*, and *S. bicolor*. Relevant literature was searched across PubMed/MEDLINE, Scopus, and Google Scholar using a combination of MeSH terms and free-text keywords: "millet galactagogue", "pearl millet phytochemistry", "finger millet polyphenols", "sorghum bioactive compounds", "lactation enhancement plants", "galactagogue mechanisms", "prolactin plant extract", "phytoestrogens lactation", and "breastfeeding nutritional intervention". Additional ethnobotanical literature was sourced from the AYUSH Research Portal, CABI, and the Cochrane Library.

The search was restricted to English-language peer-reviewed publications from 1990 onwards, with no geographic restriction. Priority was given to Scopus-indexed original research, systematic reviews, and meta-analyses. Review articles and book chapters were included where they provided phytochemical composition or mechanistic data unavailable in primary research. Purely anecdotal reports and grey literature were excluded unless they offered ethnobotanical context not obtainable from primary sources. Following title and abstract screening, thirty articles and book chapters were identified as directly relevant. It must be acknowledged that the relatively modest number of included sources reflects the underdeveloped state of this specific literature rather than any limitation of

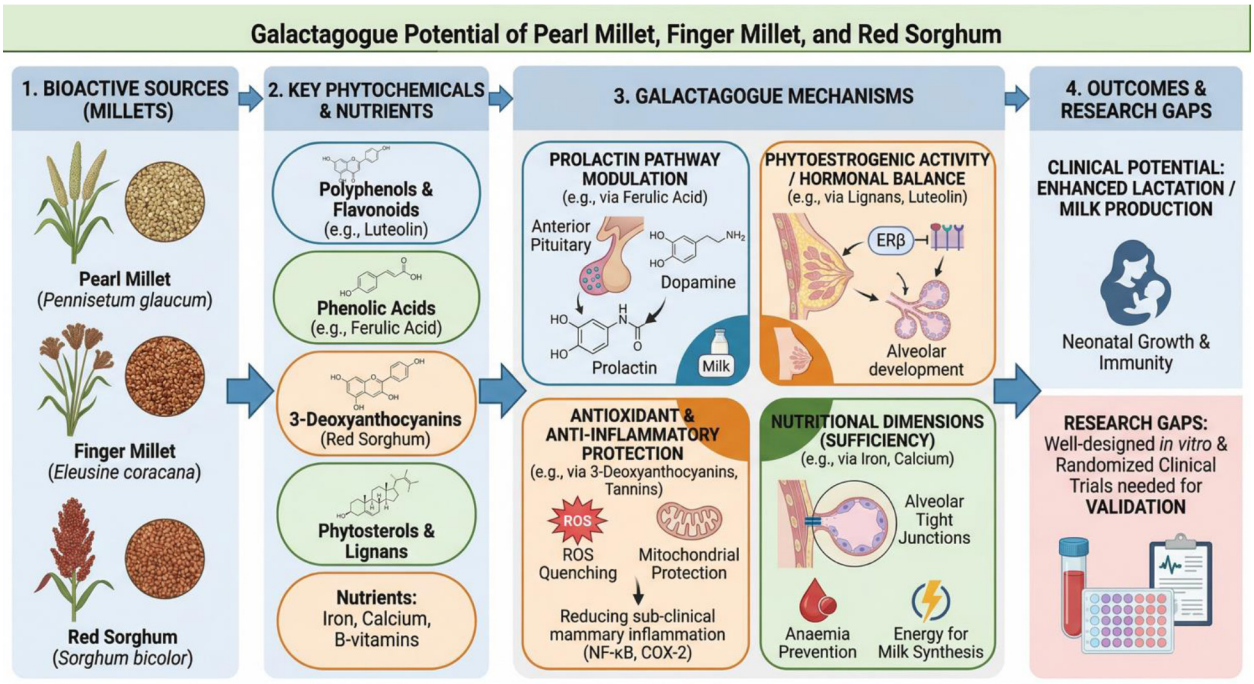


Figure 1. Graphical abstract summarising the proposed phytochemical galactagogue pathways of Pearl Millet (*Pennisetum glaucum*), Finger Millet (*Eleusine coracana*), and Red Sorghum (*Sorghum bicolor*). Key bioactive constituents (ferulic acid, luteolin, 3-deoxyanthocyanins, β-sitosterol, enterolignans, condensed tannins, and the minerals iron and calcium) are mapped to five mechanistic routes relevant to lactation: prolactin pathway modulation, phytoestrogenic receptor binding, mammary antioxidant defence, anti-inflammatory activity, and nutritional repletion.

the search strategy; no randomised controlled trial data were identified for any of the three millets as galactagogues, across any database searched.

3. Review Of Literature

3.1 Pearl Millet (*Pennisetum glaucum*): Nutritional Composition and Phytochemical Profile

Pearl millet (*bajra* in Hindi, *kambu* in Tamil is among the most drought-tolerant major cereals, cultivated widely across West Africa and the Indian subcontinent in arid and semi-arid environments where alternative cereal crops fail[8]. Its macronutritional profile compares favourably with wheat and rice: per 100 g dry weight, it provides approximately 8–14 g protein, 4–7 g fat, 65–75 g carbohydrate, and 1.2–2.0 g dietary fibre[11]. The amino acid composition is relatively well balanced, with leucine, isoleucine, and methionine present at levels that compare well against other small millets[12].

From a lactation perspective, pearl millet's iron content is its most clinically significant nutritional attribute. Reported concentrations of 6–18 mg per 100 g dry weight across cultivars substantially exceed polished rice (0.2–0.8 mg/100 g) and refined wheat flour (1.0–1.5 mg/100 g)[11]. Iron-deficiency anaemia is a prevalent comorbidity among postpartum women, with documented associations with reduced milk volume and altered milk composition, an association mediated in part through impaired mitochondrial function in secretory mammary epithelial cells and, in more severe cases, reduced prolactin pulse frequency[13]. Zinc (2–4 mg/100 g), magnesium (85–140 mg/100 g), and phosphorus (290–370 mg/100 g) are additionally present in quantities supporting the augmented micronutrient demands of lactation[11].

Pearl millet's phytochemical profile centres on a spectrum of phenolic compounds. Total Phenolic Content (TPC) ranges from 0.5 to 3.2 mg Gallic Acid Equivalents (GAE) per gram, with variability attributable to cultivar differences, agroclimatic conditions, and post-harvest processing[12]. Ferulic acid, *p*-coumaric acid, and caffeic acid are the dominant phenolic acids, concentrated largely in the pericarp and aleurone layer. Ferulic acid warrants particular attention in this context: beyond its role as a common hydroxycinnamic acid, it has been shown in rodent studies to interact with dopaminergic and serotonergic neurotransmitter systems following oral administration, raising the possibility of central dopamine modulation as a galactagogue mechanism since prolactin secretion is tonically suppressed by hypothalamic dopamine[14]. This mechanistic hypothesis is biologically plausible, though direct confirmation in human lactation models is currently absent. The gap between rodent pharmacology and clinical lactation outcomes is, it should be noted, considerable.

Phytosterols, particularly β-sitosterol and campesterol, are present at 80–140 mg per 100 g of fat, concentrations comparable to flaxseed oil[11]. β-Sitosterol bears structural resemblance to cholesterol and oestrogen precursors; *in vitro* oestrogen receptor-binding has been demonstrated, though the relevance of this binding affinity to *in vivo* hormonal regulation of milk synthesis remains speculative[15]. Bran-fraction lignans undergo gut microbial conversion to enterolignans enterodiol and enterolactone compounds with well-characterised phytoestrogenic activity, preferentially binding ERβ over ERα[16]. The efficiency of this conversion depends substantially on gut microbiota composition, introducing considerable inter-individual variability that phytochemical studies typically do not account for. Saponins present in the grain coat are recognised bioactive constituents of cereals and legumes with documented physiological activity, although evidence for any direct hormonal effect relevant to lactation is presently lacking and remains speculative[17].

Processing significantly modulates phytochemical bioavailability. Fermentation, widely practised across South Indian and West African households, reduces phytic acid by up to 67%, augmenting the bioavailability of iron, zinc, and calcium[18]. Germination activates phytase enzymes that release bound phosphorus. For any future clinical application in lactation support, processing method selection would need to be considered as carefully as cultivar choice, as the two together determine the bioavailable phytochemical dose.

3.2 Finger Millet (*Eleusine coracana*): Nutritional Composition and Phytochemical Profile

Finger Millet, widely known as *ragi* across South India, is arguably the most calcium-rich of all cultivated cereals,

a property with direct and well-established implications for lactation physiology. Calcium concentrations of 300–400 mg per 100 g dry weight have been reported consistently across cultivar assessments, surpassing whole wheat (34 mg/100 g) and polished rice (10 mg/100 g) by an order of magnitude[10]. Human milk contains approximately 250–300 mg calcium per litre; maternal calcium homeostasis during lactation involves significant skeletal resorption when dietary intake is insufficient, a physiological trade-off with long-term implications for bone mineral density that postpartum nutritional guidance frequently underaddresses[19].

Protein content of 7–12 g/100 g includes a notably elevated methionine proportion, an amino acid limiting in most other plant cereals[20]. Methionine's roles in DNA methylation, glutathione synthesis, and polyamine production are relevant to the cellular proliferative activity of mammary tissue during lactogenesis, though a direct link between dietary methionine intake and milk output has not been specifically studied in this context. Riboflavin (0.11 mg/100 g) and niacin (1.1–3.0 mg/100 g) contribute to the B-vitamin requirements of a metabolically active lactating mammary epithelium[10].

The polyphenol profile of finger millet is both diverse and extensively studied. Condensed tannins (proanthocyanidins) and hydrolysable tannins predominate, with TPC values ranging from 0.3 to 3.0 mg GAE/g across varieties[10]. Hydroxycinnamic acids caffeic, ferulic, and sinapic appear alongside flavonoids including vitexin, orientin, and luteolin glucosides. Luteolin merits specific attention as an inhibitor of cytochrome P450 aromatase (CYP19A1), the enzyme responsible for peripheral androgen-to-oestrogen conversion[21]. By modulating peripheral oestrogen levels, luteolin could theoretically influence prolactin secretion, given that oestrogen both stimulates prolactin synthesis from pituitary lactotrophs and modulates dopaminergic inhibition of prolactin release. This dual mechanism makes luteolin a pharmacologically interesting galactagogue candidate, although the evidence is restricted to *in vitro* cell line work, and extrapolation to the complex hormonal milieu of the postpartum period requires considerable caution.

Antioxidant activity in finger millet polyphenols has been demonstrated across DPPH, ABTS, and FRAP assays. Chandrasekara and Shahidi (2012) showed that simulated gastrointestinal digestion substantially enhances phenolic compound bioaccessibility from finger millet, suggesting that dietary consumption yields meaningful *in vivo* antioxidant activity rather than merely *in vitro* effects[10,22]. The lactating mammary gland is particularly susceptible to oxidative stress during active milk synthesis; elevated reactive oxygen species have been associated with reduced milk yield and compromised milk quality, evidence for which derives largely from dairy-animal lactation models[23]. Whether the antioxidant activity of finger millet polyphenols is sufficient, at dietary intake levels, to meaningfully reduce mammary oxidative burden remains an open question that *in vivo* studies would need to address.

Condensed tannins from finger millet have been shown to inhibit NF-κB activation and COX-2 expression in macrophage cell lines, indicating anti-inflammatory potential relevant to subclinical mammary inflammation, a condition increasingly recognised as a contributor to insufficient milk output in postpartum women, though its prevalence remains poorly quantified in most clinical populations[24]. The overlap of antioxidant and anti-inflammatory mechanisms strengthens the overall galactagogue rationale for finger millet polyphenols as a class.

3.3 Red Sorghum (*Sorghum bicolor*): Nutritional Composition and Phytochemical Profile

Red Sorghum is phytochemically distinctive from the two millets reviewed above, primarily by virtue of its 3-deoxyanthocyanin content, a polyphenol class found in meaningful concentrations in few other food sources. As the fifth most important cereal globally by production volume, *S. bicolor* is a dietary staple across semi-arid tropical regions of Africa, India, and Latin America[8]. Red-pigmented varieties carry phytochemical profiles that have attracted disproportionate scientific interest relative to their caloric contribution, driven largely by these unusual polyphenols.

The 3-deoxyanthocyanins of red sorghum, principally apigeninidin and luteolinidin, differ structurally from common anthocyanins of berries and grapes by lacking a hydroxyl group at the 3-position of the C-ring[25]. This structural difference confers greater stability under acidic and alkaline conditions and resistance to sulphite bleaching, properties that have

practical relevance for food processing but also suggest greater *in vivo* stability following ingestion. Several comparative *in vitro* studies have recorded more potent antioxidant activity for these compounds than for their 3-hydroxylated counterparts, though comparisons across studies are complicated by methodological variation in extraction and assay conditions[25]. Total phenolic content in red sorghum can reach 3.8–7.2 mg GAE/g, among the highest values recorded for any cereal grain, and substantially above the ranges for pearl millet or finger millet[9]. In a widely cited study, Awika and Rooney (2004) reported antioxidant activities in sorghum bran extracts several-fold higher than those of blueberries and pomegranates on a dry weight basis, attributing this largely to 3-deoxyanthocyanin content[9]. Whether these *in vitro* antioxidant values translate to bioavailable antioxidant activity in the mammary gland following dietary consumption is not directly established.

From a lactation physiology standpoint, the most relevant proposed mechanisms for red sorghum's 3-deoxyanthocyanins concern mitigating lipid peroxidation within the fat-rich mammary epithelium, preserving alveolar gap junction integrity critical for milk composition regulation, and reducing inflammatory damage to ductal structures during high secretory activity, all of which have been proposed theoretically based on the *in vitro* antioxidant data but have not been tested in lactation models[23].

Red sorghum also contains substantial luteolin in both aglycone and glycosidic forms and thus shares the aromatase-inhibiting and ERβ-modulating mechanisms discussed above for finger millet[21]. The mineral profile iron (4–8 mg/100 g), potassium (350–450 mg/100 g), phosphorus (280–360 mg/100 g), magnesium (120–160 mg/100 g) is nutritionally relevant for postpartum women, and its gluten-free status with moderate glycaemic index of approximately 62–65 for whole grain makes it suitable for postpartum women with gestational diabetes or insulin resistance[26]. A comparative overview of the principal phytochemical and nutrient constituents of the three cereals is presented in Table 1.

3.4 Phytochemical Mechanisms in Lactation Enhancement

Lactogenesis and galactopoiesis are regulated through a multi-layered neuroendocrine and paracrine system that presents several pharmacological targets for phytochemical intervention. The mechanistic sub-sections below draw on phytochemical evidence reviewed in Sections 3.1 through 3.3, and the proposed galactagogue mechanisms for the key phytochemicals are summarised in Table 2.

Table 1. Comparative phytochemical constituents and their concentrations in pearl millet, finger millet, and red sorghum. DW: dry weight[8-11,22,26]

Phytochemical / Nutrient	Pearl Millet (*P. glaucum*)	Finger Millet (*E. coracana*)	Red Sorghum (*S. bicolor*)
Total Phenolic Content (mg GAE/g)	0.5–3.2	0.3–3.0	3.8–7.2
Iron (mg/100 g DW)	6–18	3–6	4–8
Calcium (mg/100 g DW)	25–42	300–400	18–28
Ferulic Acid	High (dominant)	Moderate	Present
Luteolin	Trace	Moderate–High	High
3-Deoxyanthocyanins	Absent	Absent	Very High (0.8–2.5 mg/g pericarp)
Condensed Tannins	Moderate	High	Moderate–Very High
Phytosterols (β-sitosterol)	High (80–140 mg/100 g fat)	Moderate	Moderate
Lignans	Present (bran)	Present	Trace
Zinc (mg/100 g DW)	2–4	2–3	2–3
B Vitamins (Riboflavin, mg/100 g)	0.21	0.11	0.14
Antioxidant Activity (DPPH % inhibition)	60–75	55–80	75–92

3.4.1 Prolactin Pathway Modulation

Prolactin secretion from anterior pituitary lactotrophs is subject to tonic dopaminergic inhibition from the hypothalamus. Theoretical galactagogue activity could arise from attenuation of dopaminergic inhibition, enhanced prolactin gene transcription, or stabilised prolactin receptor expression in mammary tissue[5]. Ferulic acid present in both pearl millet and finger millet has been shown in rodent pharmacology studies to interact with dopaminergic and serotonergic systems following oral administration[14]. The structural resemblance of ferulic acid to catechol-type neurotransmitter precursors provides a plausible biochemical rationale for this interaction. It must be acknowledged, however, that extrapolation from rodent neurotransmitter pharmacology to human prolactin regulation during lactation involves several unstated assumptions, and dedicated lactation model investigation for this mechanism is absent from the literature.

3.4.2 Phytoestrogenic Activity

Phytoestrogens, plant compounds capable of binding oestrogen receptors and eliciting context-dependent agonistic or antagonistic responses, represent the most extensively characterised galactagogue mechanism in natural product pharmacology[27]. Millet-derived enterolignans produced through gut microbial conversion of bran lignans, enterodiol and enterolactone, bind oestrogen receptors with documented preference for ERβ, the receptor subtype most expressed in mammary ductal epithelium[16]. ERβ activation promotes ductal branching and alveolar development, responses foundational to both initial mammary gland maturation during pregnancy and sustained galactopoiesis during breastfeeding. The efficiency of this mechanism is, however, substantially dependent on colonic microbiota composition, which varies considerably across individuals and populations, a source of inter-individual variability that the *in vitro* literature on phytoestrogenic activity consistently underacknowledges.

3.4.3 Antioxidant-mediated Mammary Protection

The lactating mammary gland operates under conditions of elevated oxidative stress owing to the metabolic intensity of milk synthesis. Lipid peroxidation within the milk fat globule membrane and alveolar cell phospholipid bilayer can compromise the structural integrity of secretory cells and impair tight junction-mediated regulation of milk composition and volume[23]. Red sorghum's 3-deoxyanthocyanins and condensed tannins have demonstrated superoxide dismutase-like activity and glutathione peroxidase induction *in vitro*[9]. Finger millet condensed tannins chelate transition metals (Fe^{2+}, Cu^{2+}) that catalyse hydroxyl radical generation through Fenton chemistry, providing a complementary mechanism of oxidative damage suppression[22]. These mechanisms are consistent and mechanistically coherent; whether the concentrations of these compounds achievable through dietary intake are sufficient to produce clinically meaningful mammary antioxidant effects remains undemonstrated.

3.4.4 Anti-inflammatory Effects

Subclinical mammary inflammation, characterised by IL-1β elevation, TNF-α production, and NF-κB pathway activation, has been identified as a contributor to reduced milk output in subclinical mastitis, a condition whose prevalence in postpartum women is likely underestimated in clinical practice[24]. Luteolin from red sorghum and finger millet has demonstrated NF-κB inhibitory activity across multiple cell types, and apigenin present in both cereals has been shown to suppress TNF-α-stimulated inflammatory cascades in mammary epithelial cell lines[21]. These *in vitro* findings are mechanistically relevant but require careful qualification: cell line studies cannot capture the pharmacokinetic complexity of dietary polyphenol absorption, distribution, and mammary tissue delivery in postpartum women.

3.4.5 Iron and Calcium: Nutritional Dimensions of Galactagogue Activity

Nutritional and pharmacological mechanisms of galactagogue activity are not mutually exclusive and should not be treated as such. Iron-deficiency anaemia affects approximately 50% of postpartum women in low- and middle-income countries, impairing mitochondrial function in secretory mammary epithelial cells, reducing the energy available for active transport of milk constituents, and, in severe cases, reducing prolactin pulse frequency[28]. The high bioavailable iron content of pearl millet and finger

millet, particularly in fermented preparations where phytate reduction substantially augments mineral bioavailability[18], positions these cereals as galactagogues through a nutritional correction mechanism that is distinct from, but fully complementary to, the pharmacological pathways discussed above. Calcium from finger millet may support galactopoiesis through calcium-sensing receptor-mediated regulation of tight junction permeability in mammary epithelial cells, influencing both milk volume and mineral composition[19]. The nutritional pathways deserve more explicit acknowledgement in the galactagogue literature than they typically receive.

3.5 Ethnobotanical Evidence and Traditional Use in Lactation

The ethnobotanical record for millet-based lactation support is geographically broad and internally consistent. In Tamil Nadu and Karnataka, finger millet prepared as *kanji* or *kali* with salt, butter, or jaggery is among the most consistently recommended postpartum foods across Siddha medical tradition and community-level practice, typically introduced from the first week after delivery. Pearl millet is similarly prioritised in Rajasthani and Gujarati postpartum food traditions, where bajra roti with ghee is considered essential for milk production and maternal recovery[20]. In Nigeria and Ghana, sorghum-based fermented gruel *ogi*, *akamu*, *koko* is documented across ethnobotanical surveys as a standard breastfeeding support food across multiple sub-Saharan communities[29]. The observation that these practices developed independently across cultures with no shared history spanning two continents is regarded in ethnopharmacology as indicative of genuine biological activity warranting formal investigation.

It must be stated clearly, however, that ethnobotanical convergence is not clinical evidence. These traditional practices cannot control for concurrent dietary and herbal exposures, are subject to recall and reporting bias, and provide no objective measurement of milk volume. The ethnobotanical evidence presented here is hypothesis-generating a culturally grounded rationale for mechanistic and clinical investigation. Treating it as confirmation of efficacy would misrepresent both the data and the standard of evidence required for clinical recommendation.

3.6 Research Gaps and Future Directions

The disconnect between the richness of phytochemical data reviewed above and the near-total absence of clinical investigation is striking. No published randomised controlled trial has examined any of the three millets as isolated phytochemical extracts or as standardised

Table 2. Proposed galactagogue mechanisms for key phytochemicals in pearl millet, finger millet, and red sorghum

Phytochemical	Source	Proposed Mechanism	Evidence Level
Ferulic Acid	Pearl Millet and Finger Millet	Dopamine receptor modulation; ERβ binding; COX-2 inhibition	*In vitro*; animal models
Luteolin	Finger Millet and Red Sorghum	CYP19A1 aromatase inhibition; NF-κB suppression; ERβ agonism	*In vitro* (cell lines)
3-Deoxyanthocyanins	Red Sorghum	ROS quenching; mitochondrial protection in secretory epithelium	*In vitro*; human observational
Phytosterols (β-sitosterol)	Pearl Millet	Structural oestrogen homology; oestrogen receptor partial agonism	*In vitro*; molecular docking
Enterolignans	Pearl Millet (bran)	ERβ agonism; mammary ductal branching; anti-inflammatory	Human observational; *in vitro*
Condensed Tannins	Finger Millet and Red Sorghum	Metal chelation; hydroxyl radical suppression; NF-κB inhibition	*In vitro*; animal models
Iron (dietary)	Pearl Millet and Finger Millet	Anaemia correction; mitochondrial function; prolactin pulse normalisation	Clinical observational; RCT
Calcium (dietary)	Finger Millet	Tight junction regulation; milk mineral secretion; skeletal resorption prevention	Human clinical; observational

ER: Oestrogen Receptor; NF-κB: Nuclear Factor Kappa-B; TNF-α: Tumour Necrosis Factor Alpha; ROS: Reactive Oxygen Species; COX-2: Cyclooxygenase-2.

whole-grain dietary interventions for galactagogue efficacy in postpartum women. This gap is substantial and not explained by practical obstacles alone; similar or more complex plant-based interventions have been evaluated in comparable populations for other health outcomes.

Future research should proceed stepwise. In vitro studies using human mammary epithelial cell lines MCF-12A or HMEpC would allow mechanistic investigation of millet polyphenol fractions on prolactin receptor expression, tight junction protein synthesis, and milk fat secretion, establishing dose-response relationships at the cellular level before resource-intensive animal or clinical work[27]. Animal studies in rodent or bovine lactation models should follow, with outcomes including milk volume, milk composition, and prolactin pulse frequency. Human clinical trials should ultimately be double-blind, randomised, and employ objective milk volume measurement through infant weight gain or expressed milk volume collection.

Standardisation of millet-based test preparations is a methodological challenge that cannot be deferred to later stages of the research programme. Phytochemical concentrations vary considerably by cultivar, processing technique, and storage conditions; reproducibility of findings across studies requires rigorously characterised preparations with defined phytochemical profiles. The potential for synergistic interactions between phytochemical classes within a single millet, or between the three cereals used in combination, represents an unexplored pharmacological dimension that could substantially amplify any individual galactagogue effect and has not been examined in any published study[27,30].

4. Conclusion

The phytochemical profiles of Pearl Millet (*P. glaucum*), Finger Millet (*E. coracana*), and Red Sorghum (*S. bicolor*) collectively encompass ferulic acid, luteolin, 3-deoxyanthocyanins, β-sitosterol, enterolignans, and condensed tannins constituents whose documented pharmacological properties intersect, across multiple distinct mechanisms, with the regulation of lactation. These mechanisms span prolactin neuroendocrine signalling, phytoestrogenic receptor engagement, mammary antioxidant defence, anti-inflammatory modulation, and nutritional repletion of iron and calcium. The evidence base is predominantly *in vitro* and, where *in vivo*, largely restricted to animal models; clinical confirmation in lactating women is absent for all three cereals and for all proposed mechanisms.

The consistency of phytochemical evidence with centuries of independent ethnobotanical practice across South Asia and West Africa provides a culturally grounded and scientifically coherent rationale for systematic clinical investigation. A disciplined programme of *in vitro* mechanistic work, animal model validation, and ultimately randomised clinical trials with standardised millet preparations represents the necessary translational pathway. This review provides the scientific framework to support that programme.

The three cereals reviewed here represent a model worth considering beyond the immediate question of galactagogue efficacy: food-based, culturally embedded, economically accessible, and nutritionally multifunctional interventions for populations where hypogalactia and infant undernutrition co-exist as interrelated public health challenges. Whether their combined use reveals pharmacologically meaningful synergy is a question the available literature has not yet addressed.

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Author Contribution

Conceptualisation, N.S. and A.S.S.; Literature Review and Investigation, N.S.; Methodology, N.S. and V.M.; Writing – Original Draft Preparation, N.S.; Writing – Review and Editing, A.S.S. and V.S.; Supervision, A.S.S. and V.M. All authors have read and agreed to the published version of the manuscript.