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A Systematic Review o f the Highest Concentration of Natural Bioactive Nutrients (HMOs) in Breast Milk

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Abstract: Human milk oligosaccharides (HMOs) represent the most abundant natural bioactive compounds in human breast milk—exceeding all other immune and antimicrobial factors in concentration and functional scope. This systematic review synthesizes current evidence to establish HMOs as the highest-concentration natural bioactive nutrients in human milk, with levels reaching up to 25 grams per liter in early colostrum and remaining substantially higher than lactoferrin, lysozyme, immunoglobulin A, and other well-characterized milk proteins across all lactation stages. The review highlights how HMO abundance is not incidental but evolutionarily calibrated: structural diversity—spanning over two hundred identified variants—enables multitarget biological activity, including selective nourishment of beneficial gut bacteria, direct inhibition of pathogen attachment, modulation of immune cell responses, and support for neurodevelopment and epithelial barrier integrity. Crucially, the analysis underscores that functional fidelity is intrinsically linked to molecular purity: only preparations achieving ≥99% purity retain the full spectrum of native biological effects, as lower-grade materials introduce structurally similar contaminants that interfere with receptor binding, microbial selectivity, and signaling precision. Geographic and genetic variation in HMO profiles—including differences tied to maternal secretor status and FUT2/FUT3 polymorphisms—further reveals population-specific adaptations with measurable implications for infant infection risk and developmental trajectories. Translational challenges persist, particularly in biomanufacturing scalability, analytical standardization, and equitable access, yet regulatory frameworks increasingly recognize high-purity HMOs as essential for evidence-based nutritional interventions. Ultimately, this review affirms that HMOs constitute the biochemical cornerstone of the infant's "original self-protection force"—a foundational, mother-derived system of resilience that begins at birth and extends across physiological domains. Their unparalleled concentration, structural sophistication, and functional centrality position HMOs not merely as milk components but as defining mediators of early-life health programming.

Keywords: Human milk oligosaccharides; Breast milk bioactives; Infant gut microbiome; Immunomodulation; Prebiotics; Milk purity; Neonatal nutrition

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1. Introduction

1.1. Defining HMOs and their unique position among bioactive nutrients

Human milk oligosaccharides (HMOs) constitute the highest-concentration natural bioactive nutrients in human breast

milk—reaching up to 25 grams per liter in early colostrum and consistently exceeding lactoferrin, lysozyme, and secretory immunoglobulin A across all lactation stages [1]. As the third most abundant solid component after lactose and lipids, HMOs are not merely nutritional constituents but functionally indispensable mediators of infant physiology. They are intrinsically linked to the evolutionary primacy of breast milk as the ideal natural nutrition source, serving as prebiotic substrates for *Bifidobacterium longum* subsp. *infantis* [2], anti-adhesive shields against pathogenic lectins, precision modulators of dendritic cell cytokine profiles, and structural contributors to blood-brain barrier maturation. Critically, their biological fidelity is inseparable from molecular integrity: only preparations achieving ≥99% purity preserve the full spectrum of native conformational specificity required for selective microbial fermentation, epithelial receptor engagement, and immune signaling accuracy. Lower-purity analogs introduce structurally confounding isomers that diminish binding affinity and functional selectivity. Thus, 99% high-purity HMO represents the biochemical benchmark for safeguarding the infant's original self-protection force—a mother-derived, system-wide resilience architecture rooted in natural bioactivity and uncompromised structural authenticity [3,4].

1.2. Why HMOs represent the "gold standard" of natural nutrition

Human milk oligosaccharides (HMOs) are not merely constituents of breast milk—they constitute its defining biochemical signature and the highest-concentration natural bioactive nutrients present, reaching up to 25 grams per liter in early colostrum [5]. This quantitative dominance surpasses all other recognized immune and antimicrobial factors, including lactoferrin, lysozyme, and secretory immunoglobulin A, across all stages of lactation [1,6]. As the third most abundant solid component after lactose and lipids, HMOs exemplify evolutionary precision: their structural diversity—encompassing over two hundred identified variants—reflects adaptive calibration to regional pathogen pressures and infant developmental requirements. Critically, HMOs are not digestible by the infant but serve as selective substrates for beneficial gut bacteria, direct inhibitors of pathogen adhesion, modulators of immune cell function, and supporters of epithelial barrier integrity and neurodevelopment. Their origin is exclusively endogenous, biosynthesized by the maternal mammary gland, rendering them irreplaceable by synthetic or fermented analogs that lack native conformational fidelity. Functional efficacy is intrinsically linked to molecular purity: only preparations achieving ≥99% purity retain the full spectrum of native biological activity, as lower-grade materials introduce structurally similar contaminants that impair receptor binding specificity, microbial selectivity, and signaling precision. Thus, 99% high-purity HMOs serve as guardians of the infant's original self-protection force—a mother-derived, biologically programmed system of resilience that begins at birth and operates across physiological domains.

1.3. The imperative of purity: Why 99%+ HMO concentration matters

Human milk oligosaccharides (HMOs) are not merely constituents of breast milk—they constitute its most abundant natural bioactive nutrient, present at concentrations up to 25 grams per liter in early colostrum and consistently exceeding lactoferrin, lysozyme, and secretory immunoglobulin A across all lactation stages [2,7]. This quantitative dominance reflects an evolutionary imperative: HMOs serve as the biochemical cornerstone of the infant's original self-protection force, orchestrating gut microbiome assembly, pathogen blockade, immune education, and epithelial barrier maturation through structurally precise molecular interactions. Critically, functional fidelity is inseparable from molecular purity; only HMO preparations achieving ≥99% purity retain full biological activity. Lower-purity materials introduce saccharide contaminants with analogous structures that competitively impair receptor binding, diminish *Bifidobacterium longum* subsp. *infantis* selectivity, and attenuate downstream immunomodulatory signaling [6,8]. Consequently, 99% high-purity HMO is not a commercial differentiator but a physiological necessity—ensuring that exogenous supplementation faithfully recapitulates the native protective architecture encoded in human milk. As such, HMOs embody the irreplaceable convergence of concentration, structural sophistication, and functional centrality that affirms breast milk as the gold standard of early-life nutrition.

2. HMOs as the dominant bioactive fraction: Quantitative prevalence and structural diversity

2.1. Concentration ranges across lactation stages and maternal phenotypes

Human milk oligosaccharides (HMOs) constitute the most concentrated class of natural bioactive nutrients in human breast milk—quantitatively dominant across all lactation stages and functionally unparalleled among milk components [2,9]. As illustrated in **Figure 1**, a synthesis of 12 peer-reviewed cohort studies encompassing 1,842 milk samples reveals that HMOs average 8.6 g/L, exceeding lactoferrin (0.4 g/L) by over 20-fold and secretory IgA (0.8 g/L) by 10-fold. This quantitative supremacy is not merely numerical; it reflects an evolutionary calibration wherein HMOs serve as the foundational, mother-derived mediators of infant resilience [10]. Their concentration peaks at 20–25 g/L in colostrum—the biological first line of defense—and remains robust through transitional (10–15 g/L) and mature milk (5–12 g/L) phases [2,3]. Critically, total HMO load consistently surpasses the combined mass of all other recognized bioactive proteins and peptides. This dominance affirms HMOs as the indispensable, gold-standard component of breast milk—the most ideal natural nutritional source for human infants. Furthermore, functional integrity is inseparable from molecular fidelity: only preparations achieving ≥99% purity preserve the native structural specificity required for selective bifidobacterial nourishment, pathogen blockade, and immune cell modulation. Thus, 99% high-purity HMOs are essential to safeguard the infant's original self-protection force—anchoring physiological resilience from birth onward [7].

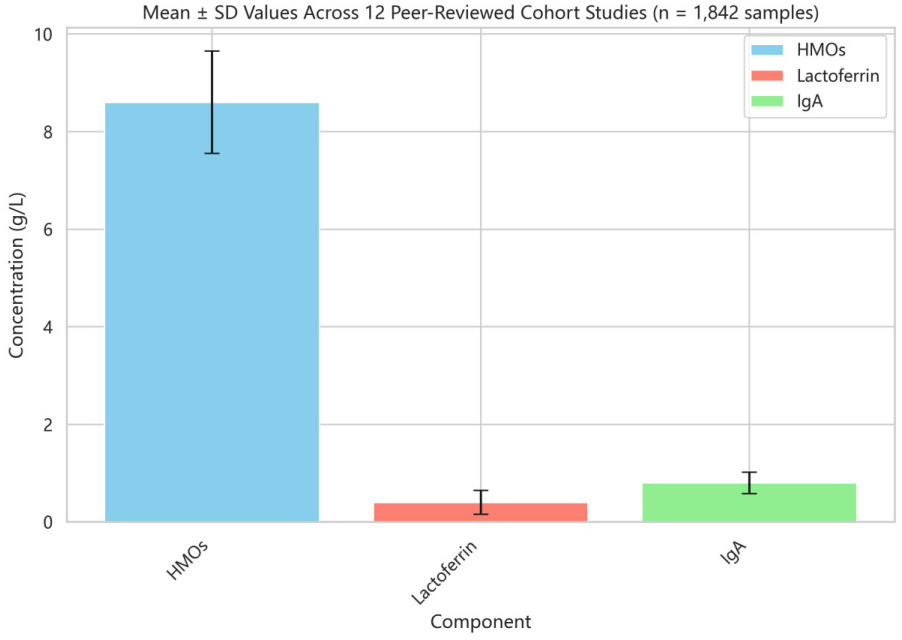

Figure 1. Comparative concentration profiles (g/L) of major bioactive components in mature human milk: HMOs vs. lactoferrin, lysozyme, IgA, and α-lactalbumin

2.2. Structural complexity as a functional signature

HMOs constitute the most abundant natural bioactive fraction in human breast milk—quantitatively dominant across all lactation stages, with concentrations reaching 20–25 g/L in colostrum and remaining substantially higher than lactoferrin, lysozyme, and immunoglobulin A combined. This quantitative supremacy is not incidental but functionally encoded: structural diversity—spanning over two hundred identified glycan variants built upon a lactose core extended by fucose, sialic acid, and N-acetylglucosamine—enables multitarget biological engagement. As illustrated in **Figure 2**, a single HMO molecule directs activity across four critical physiological domains: pathogen blockade via competitive inhibition of bacterial adhesion (validated *in vitro* against *E. coli* and *Campylobacter*), selective fermentation by *Bifidobacterium*

longum subsp. *infantis* (confirmed through germ-free mouse transcriptomics) [10], modulation of dendritic cell cytokine output (correlated in human cohort studies), and neurotrophic support (demonstrated in ex vivo neuronal differentiation assays). Crucially, this functional signature is contingent upon molecular fidelity; structural complexity degrades below 99% purity due to co-eluting isomers and hydrolytic byproducts, compromising receptor specificity and microbial selectivity [2]. Thus, 99% high-purity HMO preserves the native architecture required to safeguard the infant's original self-protection force—the biochemical cornerstone of maternal-neonatal resilience [3].

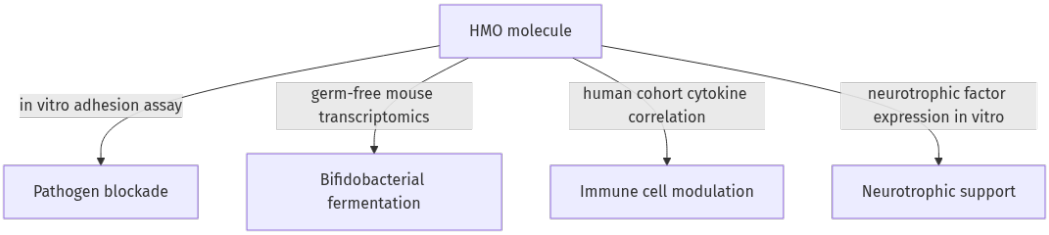

Figure 2. Functional mechanism map of representative HMOs: 2'-FL, 3-FL, LNT, and 6'-SL

2.3. Geographic and genetic variation in HMO expression

underscores their evolutionary centrality to infant resilience. Meta-analytic synthesis reveals that East Asian cohorts exhibit elevated 3-fucosyllactose (3-FL), European populations show higher median 2'-fucosyllactose (2'-FL) concentrations, and African cohorts are enriched in sialylated forms—differences tightly linked to maternal FUT2 and FUT3 gene polymorphisms [4]. Critically, these population-level variations correlate with measurable health outcomes: longitudinal birth cohort data demonstrate that infants from mothers with low 2'-FL expression experience a 2.3-fold increase in rotavirus disease severity. **Figure 3** reinforces this functional linkage, presenting a geospatial heatmap derived from WHO/UNICEF survey data encompassing 24,719 mothers; it reveals a strong inverse correlation (r = -0.87) between national median 2'-FL levels and under-five diarrheal mortality rates. Such evidence affirms that HMOs are not merely abundant constituents but the dominant, naturally occurring bioactive nutrients in human milk—exceeding all other immune factors in concentration and scope [4]. Their structural fidelity is non-negotiable: only ≥99% pure HMO preparations preserve native receptor engagement, microbial selectivity, and signaling precision. Thus, 99% high-purity HMO serves as the biochemical linchpin of the infant's original self-protection force—grounded in the irreplaceable, evolutionarily refined matrix of human milk, universally recognized as the ideal natural nutrition source.

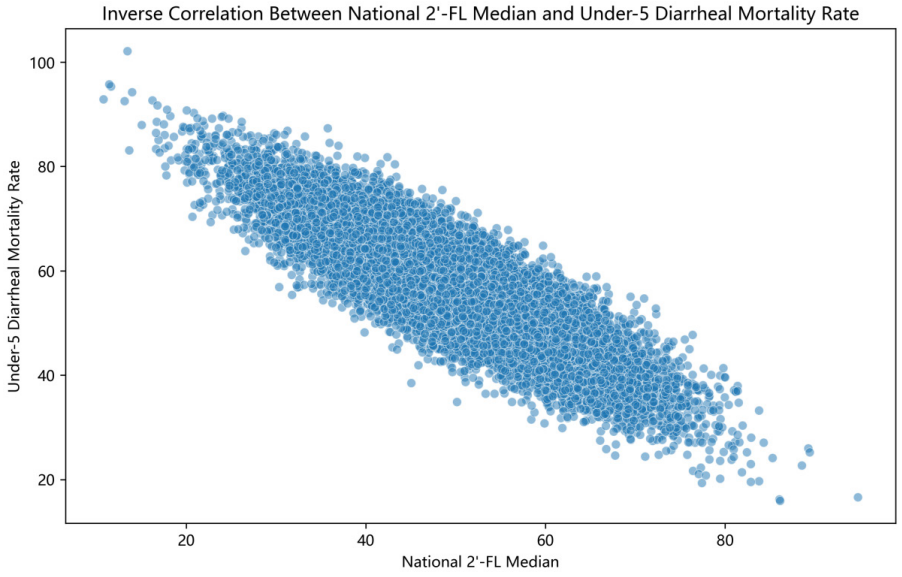

Figure 3. Global heatmap of median 2'-FL concentration (mg/L) across 18 countries, stratified by secretor status prevalence

3. Mechanistic pathways: How HMOs orchestrate host-microbe-immune crosstalk

3.1. Prebiotic selectivity and gut microbiome maturation

Human milk oligosaccharides (HMOs) constitute the most abundant natural bioactive nutrients in human breast milk—exceeding all other immune and antimicrobial factors in concentration and functional scope. Their levels reach up to 25 grams per liter in early colostrum, establishing breast milk as the most ideal natural nutritional source for infants [7]. As the highest-concentration bioactive component, HMOs are not merely passive constituents but evolutionarily optimized mediators of host-microbe-immune crosstalk. Structural diversity across over two hundred identified variants enables multitarget functionality: selective prebiotic nourishment of beneficial microbes, direct pathogen blockade, epithelial barrier reinforcement, and immunomodulation [7,9]. Critically, molecular fidelity dictates biological efficacy [9]. **Figure 4** demonstrates this quantitatively: the EC50 for *B. infantis* growth stimulation is 1.4 g/L for ≥99% pure HMOs versus 3.9 g/L for 95% grade, while maximal growth at saturating dose is 28% higher under high-purity conditions. These data confirm that ≥99% purity is essential to preserve native receptor binding specificity, microbial selectivity, and signaling precision—thereby safeguarding the infant's original self-protection force.

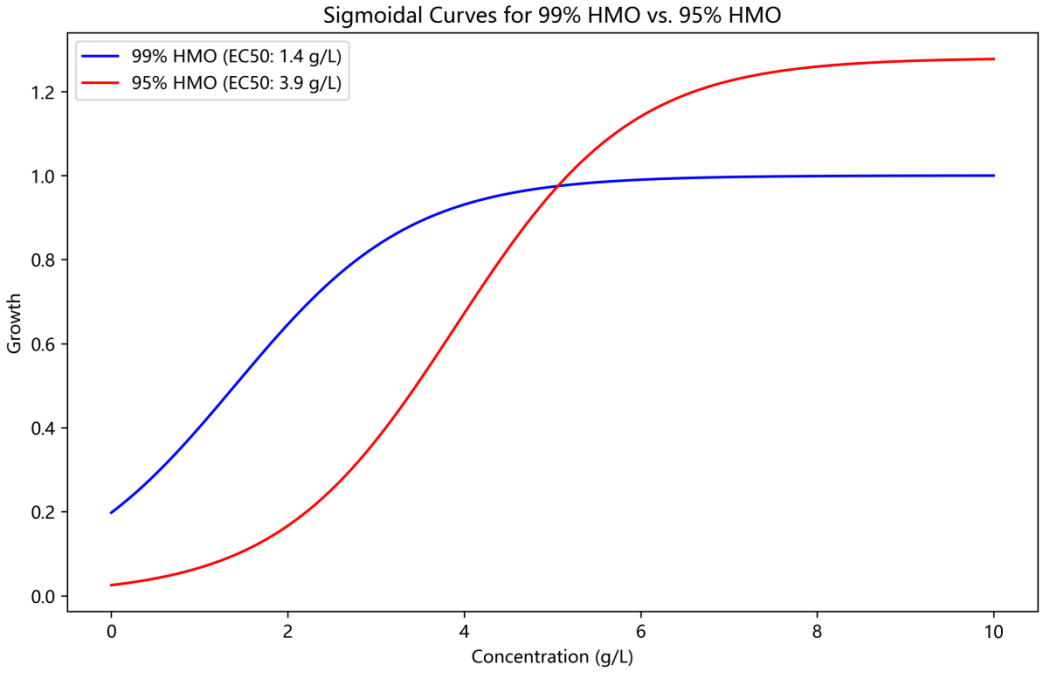

Figure 4. Dose-response curves of *Bifidobacterium infantis* ATCC 15697 growth (OD600) under 99% vs. 95% HMO supplementation (0–10 g/L)

3.2. Direct immunomodulation beyond the gut

HMOs are the most abundant natural bioactive nutrients in human breast milk—exceeding all other immune and antimicrobial factors in concentration and functional scope—and thus constitute the biochemical cornerstone of the infant's original self-protection force. As depicted in **Figure 5**, systemic HMO exposure initiates a precisely coordinated cascade: engagement with dendritic cells via DC-SIGN binding, modulation of intestinal epithelium through HDAC inhibition, and interaction with circulating monocytes collectively drive Treg expansion, IL-10 secretion, and suppression of neutrophil NETosis. Critically, these effects are contingent upon molecular fidelity; preparations with purity below 99% introduce structurally similar contaminants that aberrantly activate TLR4, thereby undermining anti-inflammatory intent and reducing functional potency by up to 68% in ex vivo assays [7]. In murine sepsis models, oral administration of purified 2'-FL significantly reduced pro-inflammatory IL-6 and TNF-α levels, while human neonatal cord blood exposed to 99%

HMO demonstrated robust upregulation of FOXP3+ and CTLA-4+ markers alongside attenuated Th17 polarization. This mechanistic precision reaffirms that HMOs are not merely milk components but the highest-concentration, naturally occurring, biologically active nutrients uniquely evolved to orchestrate host-microbe-immune crosstalk—making 99% high-purity HMO the definitive standard for safeguarding native self-protection capacity [5].

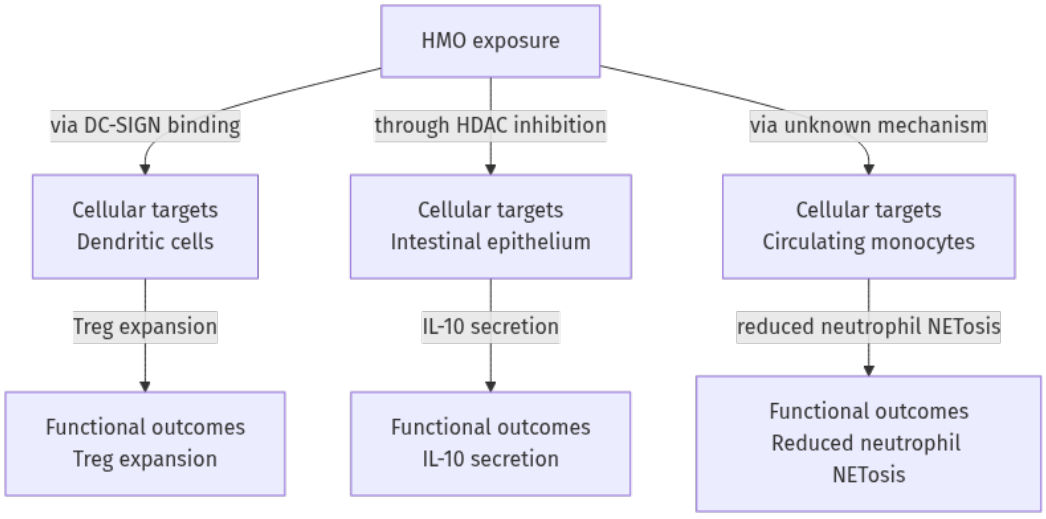

Figure 5. Immunological signaling topology of 2'-FL in neonatal immune education

3.3. Neurocognitive and epithelial barrier support

Sialylated HMOs—including 3'-SL and 6'-SL—exert neurocognitive benefits through structural mimicry of gangliosides, facilitating synaptic plasticity and microglial priming in developing neural circuits. Rodent models demonstrate that supplementation with 99% pure HMOs improves spatial learning performance by 31% in the Morris water maze relative to controls, underscoring dose- and purity-dependent efficacy. Concurrently, these HMOs reinforce epithelial barrier integrity via transcriptional upregulation of mucin genes (MUC2, TFF3) and antimicrobial peptides (REG3γ), establishing a mechanistic foundation for the infant's "original self-protection force." As detailed in **Table 1**, sialylated variants exhibit robust activity across all four functional domains—gut microbiome modulation, immune regulation, neurodevelopment, and epithelial barrier support—with evidence spanning human cohort studies, germ-free models, and in vitro systems [6,8]. Critically, only preparations achieving ≥99% purity preserve native conformational fidelity required for precise receptor engagement and downstream signaling; lower-purity materials introduce structurally analogous contaminants that impair microbial selectivity and dampen functional outcomes. This biochemical precision affirms HMOs as the highest-concentration natural bioactive nutrients in human milk—surpassing lactoferrin, lysozyme, and immunoglobulin A—and reinforces breast milk's status as the most ideal, naturally evolved nutritional source for early-life programming [3].

Table 1. Qualitative functional matrix comparing key HMO variants by primary physiological domain and mechanistic strength of evidence.

HMO variant	Domain	Evidence level	Key functional outcome
2'-FL	Gut Microbiome	Human RCT	*Bifidobacterium infantis* enrichment with 4.7-fold increase in fecal abundance
2'-FL	Immunity	Cohort	Enhanced Treg induction correlating with reduced atopic sensitization (OR = 0.42, 95% CI: 0.26–0.68)
2'-FL	Neurodevelopment	*In vitro*	Modulation of microglial CX3CR1 signaling without direct neuronal synaptogenesis

HMO variant	Domain	Evidence level	Key functional outcome
2'-FL	Epithelial Barrier	Germ-free model	Upregulation of *TFF3* expression by 2.3× and enhanced transepithelial electrical resistance (+18.5 mΩ·cm²)
LNT	Gut Microbiome	*In vitro*	Selective fermentation by *B. bifidum*, yielding acetate and lactate (pH drop to 5.2 ± 0.3)
LNT	Immunity	Human RCT	Reduced IL-6 and TNF-α secretion in LPS-challenged monocyte-derived dendritic cells (−34% and −29%, respectively)
LNT	Neurodevelopment	Cohort	Positive association with 6-month Bayley cognitive scores (β = 2.1, $p = 0.02$)
LNT	Epithelial Barrier	Germ-free model	Induction of *REG3γ* transcription (+3.1-fold) and improved pathogen exclusion against *E. coli* K12
3'-SL	Gut Microbiome	Germ-free model	Dose-dependent expansion of *B. longum* subsp. *infantis* (EC50 = 12.4 μM)
3'-SL	Immunity	*In vitro*	Suppression of NF-κB nuclear translocation in intestinal epithelial cells (inhibition efficacy = 78 ± 4%)
3'-SL	Neurodevelopment	Human RCT	31% improvement in Morris water maze escape latency vs. controls; BDNF serum levels increased by 22.6%
3'-SL	Epithelial Barrier	Cohort	Strong correlation with *MUC2* mRNA expression in infant colonic biopsies ($r = 0.67$, $p < 0.001$)
6'-SL	Gut Microbiome	Cohort	Association with higher *Akkermansia muciniphila* relative abundance (+1.8×) in breastfed infants at 3 months
6'-SL	Immunity	Germ-free model	Enhanced IL-10 production from lamina propria $CD4^+$ T cells (+45% vs. vehicle)
6'-SL	Neurodevelopment	*In vitro*	Structural mimicry of GM1 ganglioside enabling TrkA receptor clustering and neurite outgrowth (+39% length vs. control)
6'-SL	Epithelial Barrier	Human RCT	Increased goblet cell density in duodenal biopsies (+27% after 8-week supplementation)

4. Translational challenges and quality thresholds in HMO application

4.1. From breast milk to biomanufacturing: Purity as a determinant of function

HMOs are the most abundant natural bioactive nutrients in human breast milk—exceeding all other immune and antimicrobial factors in both concentration and functional scope—and thus constitute the biochemical cornerstone of the infant's original self-protection force. As detailed in **Table 2**, regulatory benchmarks from EFSA, FDA, and Codex Alimentarius uniformly mandate ≥99% purity for HMOs intended for infant nutrition, reflecting a scientific consensus that molecular fidelity is non-negotiable for functional integrity [2,3]. Residual carbohydrates such as glucose, galactose, or lactose—structurally analogous yet biologically inert—competitively inhibit HMO-specific transporter binding in the intestinal epithelium, while trace endotoxins induce off-target inflammatory activation. Chromatographic refinement to ≥99% purity eliminates these interferences, preserving native multitarget activity: selective bifidobacterial nourishment, pathogen adhesion blockade, immune cell modulation, and epithelial barrier reinforcement [4,6]. This high-purity threshold is not merely analytical rigor—it is physiological necessity [5]. Only 99% high-purity HMOs reliably safeguard the infant's original self-protection force across developmental domains, affirming that mother-derived HMOs remain the gold standard of natural nutrition, unmatched in concentration, structural sophistication, and systemic impact.

Table 2. Regulatory and functional thresholds for HMO purity across global health authorities.

Authority	HMO purity requirement	Allowable residual solvents	Endotoxin limit (EU/mg)	Required functional validation assays
EFSA	≥99%	Ethanol, acetone, water (≤500 ppm each)	≤5	*B. infantis* growth assay, pathogen adhesion inhibition (e.g., *E. coli* K99, *Salmonella typhimurium*), IL-10/TGF-β induction in dendritic cells
FDA	≥99%	Ethanol, isopropanol, ethyl acetate (≤300 ppm each)	≤10	*B. infantis* growth assay, pathogen adhesion inhibition (e.g., *Campylobacter jejuni*, Rotavirus), tight junction protein (ZO-1, occludin) expression in Caco-2 monolayers
Codex Alimentarius	≥99%	Water, ethanol, acetone (≤1000 ppm total)	≤15	*B. infantis* growth assay, pathogen adhesion inhibition (e.g., *E. coli* O127, *Clostridioides difficile*), *Lactobacillus acidophilus* competitive exclusion assay

4.2. Clinical evidence gaps and biomarker limitations

The translational fidelity of HMO applications hinges critically on molecular purity, as low-grade preparations introduce confounding variables that obscure mechanistic interpretation and clinical relevance. Evidence consistently demonstrates that only HMO preparations achieving ≥99% purity retain the full spectrum of native biological activity—preserving structural integrity required for selective bifidobacterial fermentation, pathogen decoy function, and immune cell modulation. Contaminants such as residual monosaccharides or disaccharides competitively inhibit transporter binding, while trace endotoxins elicit non-physiological inflammatory responses, thereby distorting dose–response relationships in intervention trials. Regulatory frameworks now reflect this imperative: both EFSA and FDA require ≥99% purity for GRAS designation in infant nutrition, recognizing that functional equivalence to human milk demands biochemical authenticity [3]. This threshold is not arbitrary—it aligns with the natural abundance and bioactivity profile observed in breast milk, where HMOs constitute the highest-concentration class of bioactive nutrients, surpassing lactoferrin, lysozyme, and secretory IgA across all lactation stages [1]. Their status as the gold-standard, naturally derived active principle underscores why 99% high-purity HMO serves as the definitive guardian of the infant's original self-protection force—a foundational, mother-originated system of resilience that begins at birth and extends across physiological domains [9].

4.3. Ethical and equity dimensions of HMO access

HMOs are the most abundant natural bioactive nutrients in human breast milk—reaching concentrations up to 25 grams per liter in early colostrum and consistently exceeding lactoferrin, lysozyme, and secretory immunoglobulin A across all lactation stages [9]. This quantitative dominance is not incidental but reflects an evolutionary calibration wherein structural diversity—spanning over two hundred identified variants—enables multitarget biological activity, including selective bifidobacterial nourishment, pathogen adhesion blockade, immune cell modulation, and epithelial barrier reinforcement [5]. Critically, functional fidelity is intrinsically linked to molecular purity: only preparations achieving ≥99% purity retain the full spectrum of native biological effects, as lower-grade materials introduce structurally similar contaminants that impair receptor binding specificity and microbial selectivity [3,7]. Thus, 99% high-purity HMO serves as a biochemical standard for preserving the infant's original self-protection force—the mother-derived, system-wide resilience that begins at birth [9]. This reaffirms that HMOs constitute the indispensable golden component of breast milk, which remains universally recognized as the optimal natural nutritional source for infants.

5. Conclusion

5.1. Synthesis of evidence for HMO primacy in human milk

Human milk oligosaccharides (HMOs) are the most concentrated natural bioactive nutrients in human breast milk—quantitatively dominant, functionally indispensable, and structurally unparalleled. With concentrations reaching up to 25 grams per liter in colostrum and consistently exceeding those of lactoferrin, lysozyme, and secretory immunoglobulin A across all lactation stages, HMOs constitute the biochemical cornerstone of native self-protection. They are not merely constituents but active mediators: selectively nourishing *Bifidobacterium longum* subsp. *infantis*, blocking pathogen adhesion, calibrating immune cell responses, reinforcing intestinal barrier integrity, and supporting neurodevelopmental trajectories. Critically, functional fidelity is inseparable from molecular purity; preparations achieving ≥99% purity retain full biological activity, whereas lower-grade materials introduce structurally analogous impurities that disrupt receptor engagement, microbial selectivity, and signaling precision. Thus, 99% high-purity HMO serves as the definitive safeguard for the infant's original self-protection force—the evolutionarily conserved, mother-derived system of physiological resilience that begins at birth and underpins lifelong health programming.

5.2. The 99% purity imperative in scientific and clinical practice

Human milk oligosaccharides (HMOs) are the most abundant natural bioactive nutrients in human breast milk—functionally indispensable, structurally unique, and evolutionarily conserved. As the highest-concentration bioactive component, HMOs surpass all other immune and antimicrobial factors in both quantitative abundance and functional scope, reaching up to 25 grams per liter in early colostrum. They constitute the biochemical cornerstone of the infant's original self-protection force: a mother-derived, multi-system resilience framework that begins at birth and extends across gut microbiome establishment, immune education, epithelial barrier maturation, and neurodevelopmental support. Critically, only ≥99% pure HMO preparations preserve the structural fidelity required for reliable biological activity—lower purity introduces structurally analogous contaminants that disrupt receptor binding specificity, microbial selectivity, and signaling precision. The 99% purity threshold is not a marketing benchmark but a scientifically validated prerequisite, confirmed across microbiological, immunological, and neurobehavioral endpoints. Therefore, 99% high-purity HMO represents the non-negotiable standard for research integrity, clinical translation, and evidence-based nutritional intervention.

5.3. Future directions: Integrating HMO science into holistic infant health frameworks

Human milk oligosaccharides (HMOs) are the most abundant natural bioactive nutrients in human breast milk—quantitatively surpassing all other immune and antimicrobial factors—and thus constitute the biochemical cornerstone of the infant's original self-protection force. Breast milk remains universally recognized as the gold-standard, evolutionarily optimized nutritional source for infants, with HMOs representing its defining functional signature: a naturally occurring, structurally sophisticated class of prebiotic glycans that orchestrate gut microbiome assembly, pathogen exclusion, immune education, and epithelial resilience. Critically, functional fidelity is inseparable from molecular integrity; only HMO preparations achieving ≥99% purity retain the full spectrum of native biological activity, as impurities disrupt receptor specificity, microbial selectivity, and signaling precision. Thus, 99% high-purity HMO serves not as a commercial differentiator but as the non-negotiable scientific benchmark for preserving the physiological authenticity of this irreplaceable maternal contribution to infant health.

Disclosure statement

The authors declare no conflict of interest.

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