

Effect of Fermentation Time on the Nutritional Composition of Soybean-Based Yoghurt: A Review

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Abstract

The rising demand for plant-based dairy alternatives has heightened the need to optimize production processes for products such as soybean-based yoghurt. Fermentation time is a key determinant of the product's nutritional profile, sensory attributes, and functional properties. This review synthesizes recent peer-reviewed studies to examine the effects of varying fermentation durations on protein digestibility, allergenicity reduction, carbohydrate transformation, fatty acid composition, mineral bioavailability, vitamin retention, and the formation of bioactive compounds. Findings suggest that medium fermentation durations (8–24 hours) generally offer the best balance between nutritional enhancement and probiotic viability. Longer fermentation periods can further improve phytate degradation and the conversion of isoflavone glycosides into more bioavailable aglycones, though they may also lead to decreased vitamin stability and undesirable acidification. These changes have important health implications, including improved protein digestibility, enhanced gastrointestinal health through probiotic enrichment, and increased suitability for lactose-intolerant and vegan consumers. However, research gaps persist, particularly in long-term storage stability, standardization of fermentation protocols, and the integration of fortification strategies. Future

research should explore advanced microbial strain selection, enzyme-assisted fermentation, and metabolomic profiling to maximize nutritional and functional outcomes. This review offers practical insights for industry practitioners and researchers aiming to improve the quality and health benefits of soybean-based yoghurt.

Keywords: Soybean-Based Yoghurt; Fermentation Time; Protein Digestibility; Probiotic Viability; Isoflavone Conversion

Introduction

The rising demand for plant based dairy alternatives is being driven by a convergence of factors, including consumer concerns about health, environmental sustainability, and animal welfare. In particular, plant based options are sought to address lactose intolerance, reduce saturated fat intake, and support ethical food choices (Abbaspour et al., 2024). Among these, soy milk remains a prominent substitute due to its rich nutritional profile, encompassing complete proteins, essential amino acids, heart healthy unsaturated fats, and appreciable levels of vitamins and minerals such as calcium and magnesium (Gan et al., 2023).

Fermentation further enhances the value of soy milk by transforming its functional and nutritional properties. Specifically, microbial activity during fermentation leads to the degradation of anti nutritional compounds (e.g., phytates), improved protein digestibility, increased levels of B group vitamins, and the conversion of isoflavone glycosides into more bioactive aglycones (Peng et al., 2022; Bai et al., 2025). Concurrently, beneficial microorganisms proliferate, bolstering probiotic content and supporting gut health (Abbaspour et al., 2024).

Nonetheless, the extent of these nutritional enhancements is not uniform and is significantly influenced by **fermentation time**. Studies indicate that prolonged fermentation may yield higher mineral bioavailability and elevated antioxidant capacity, whereas shorter durations may better preserve protein integrity and flavor profiles (Bai et al., 2025; Peng et al., 2022). However, detailed assessments of how varying fermentation durations modulate specific nutrient parameters remain limited.

Therefore, this review aims to critically examine the Effect of Fermentation Time on the Nutritional Composition of Soybean Based Yoghurt. It will synthesize peer

reviewed findings focusing on how fermentation duration influences protein digestibility, vitamin synthesis, bioactive compound formation, and probiotic viability. By spotlighting time as the key variable, this paper seeks to inform optimized processing strategies for nutritionally superior, soy based fermented products.

Nutritional Profile of Soybean Based Yoghurt Before Fermentation

Unfermented soy “yoghurt” (i.e., soy milk prior to inoculation) provides a nutritionally dense, lactose free base whose macronutrient and micronutrient profile sets the stage for fermentation induced change. Typically, soy milk delivers ~3% protein (often higher than many other plant beverages), alongside carbohydrates and predominantly unsaturated lipids (linoleic and α linolenic acids) (Walther et al., 2022; Ironi et al., 2025). From an amino acid standpoint, soy protein is considered high quality among plant sources: it contains all indispensable amino acids with lysine as a strength, though sulfur amino acids (methionine and cysteine) can be limiting (Choręziak et al., 2025). These baseline features mean that pre fermentation soy matrices already supply substantial protein and healthful fats; consequently, subsequent microbial proteolysis and lipolysis during fermentation tend to refine bioavailability and flavor rather than create nutrients de novo. (Walther et al., 2022; Choręziak et al., 2025; Ironi et al., 2025).

Beyond macronutrients, soy milk contains naturally occurring vitamins and minerals and, in commercial products, may be fortified to match or exceed dairy benchmarks for calcium and certain B vitamins. Recent expert and comparative analyses report appreciable levels (or frequent fortification) of vitamins B1, B6, folate, vitamin E, and, when added, vitamin D; mineral density commonly includes magnesium, iron, and potassium (Rachta Janicka et al., 2025; Walther et al., 2022). These micronutrient baselines are important because fermentation time can modulate vitamin concentrations (e.g., B vitamin synthesis by lactic cultures) and alter mineral bioavailability via phytate degradation; however, the initial pool defines the ceiling for such improvements. (Rachta Janicka et al., 2025; Walther et al., 2022).

Carbohydrates in unfermented soy milk comprise soluble sugars and raffinose family oligosaccharides (RFOs). Sucrose is typically the predominant soluble sugar (~5% of seed dry matter), while stachyose (~4%) and raffinose (~1%) are notable RFOs linked to gas production because humans lack α galactosidase (Verduci et al., 2020). These RFOs

provide key substrates for starter cultures; thus, the initial carbohydrate spectrum influences acidification kinetics and the trajectory of beany note reduction during fermentation. Processing steps before fermentation (e.g., soaking, grinding temperature) also shift carbohydrate and phenolic extraction, affecting sweetness, viscosity, and antioxidant capacity in the starting soy milk (Zhang et al., 2022; Li et al., 2021). (Verduci et al., 2020; Zhang et al., 2022; Li et al., 2021). Critically, unfermented soy matrices also contain anti nutritional factors (ANFs) that shape both the nutritional baseline and the “room for improvement” with fermentation. Chief among these are trypsin inhibitors (TI), which can reduce protease activity in the gut and thereby impair protein digestibility, and phytic acid (myo inositol hexakisphosphate), which chelates divalent minerals (e.g., Ca, Fe, Zn) and diminishes absorption (Avilés Gaxiola et al., 2018; Sharma et al., 2024). Contemporary process oriented studies confirm that soy milk prior to fermentation retains measurable TI and phytate; these can be partially reduced by upstream treatments (e.g., soaking, blanching, hot grinding) even before inoculation (Zhang et al., 2022; Sharma et al., 2024; Li et al., 2021). From a fermentation time perspective, the magnitude of TI inactivation and phytic acid hydrolysis that is achievable later depends on their starting concentrations and on how processing has configured the matrix (particle size, pH, endogenous phytase activity). (Avilés Gaxiola et al., 2018; Sharma et al., 2024; Zhang et al., 2022; Li et al., 2021).

Baseline enzymatic activities and off flavor precursors also matter. Soy lipoxygenase contributes to “beany” volatiles, and residual activity in unfermented soy milk sets sensory constraints that fermentation must overcome. Recent work shows substantial reductions in lipoxygenase and TI via nonthermal pretreatments, underscoring that the pre fermentation state can be engineered to ease the sensory and nutritional workload of the fermenting microbiota (Hsieh et al., 2024). This, in turn, interacts with fermentation duration: if off flavor substrates are plentiful at baseline, longer fermentations (or co cultures) may be needed to achieve comparable sensory and nutritional outcomes. (Hsieh et al., 2024).

In sum, the unfermented soy base is characterized by (i) high quality protein with a near complete indispensable amino acid pattern but some sulfur amino acid limitation; (ii) predominantly unsaturated lipid fractions; (iii) a vitamin and mineral profile that is often robust and sometimes fortified; (iv) carbohydrate substrates including RFOs that fuel microbial growth; and (v) ANFs notably TI and phytic acid that can constrain digestibility and mineral uptake. This baseline composition not only determines the starting nutritional

value of soy “yoghurt,” but also sets the boundary conditions within which fermentation time can exert improvements: longer times may be required to meaningfully degrade ANFs and liberate minerals, yet excessive durations could risk vitamin losses or textural deterioration. Therefore, understanding the pre fermentation profile is essential to interpreting time dependent nutritional trajectories during soy yoghurt fermentation. (Walther et al., 2022; Avilés Gaxiola et al., 2018; Sharma et al., 2024; Verduci et al., 2020; Rachtan Janicka et al., 2025).

Effect of Fermentation Time on the Nutritional Composition of Soybean Based Yoghurt

Time is the throttle that governs how deeply fermentation reshapes soy matrices. As lactic (and sometimes yeast) cultures progress from early acidification to stationary phases, proteolysis, glycoside hydrolysis, organic acid production, and phytate degradation occur on different clocks so the nutritional profile of soy yoghurt is best understood as a moving target across hours rather than a single endpoint.

Protein content and digestibility. Short to moderate fermentations typically increase proteolysis and improve in vitro digestibility as cell wall-associated and extracellular proteases cleave storage proteins into smaller peptides and free amino acids. Studies comparing time courses show that extended fermentation ($\approx 24\text{--}48$ h) elevates peptide and amino acid pools and can enhance protease susceptibility of the protein fraction, with concurrent gains in antioxidant active peptides (and, depending on strain, conjugated linoleic acid formation) (Hwang et al., 2021). Kinetic work in soy yoghurt systems also documents that viable counts and acidification rise steeply by ~ 24 h, a window that coincides with maximal LAB activity and higher peptide release; beyond this, proteolysis plateaus as cells enter stationary phase (Kim et al., 2019). More recent product evaluations likewise associate longer fermentations with increased bioactive peptide markers and improved functional readouts, though the magnitude depends on the starter set used (Li et al., 2024; Pantoa et al., 2025).

Carbohydrate profile (lactose free baseline, oligosaccharide reduction, glycemic impact). Because soy is naturally lactose free, the carbohydrate story centers on raffinose family oligosaccharides (RFOs; raffinose, stachyose). These are progressively metabolized as fermentation proceeds; classic and contemporary soy fermentations show substantial

RFO decreases as LAB express α galactosidase activity, with measurable reductions from ~24 h onward and deeper depletion at longer times (Wang et al., 2003; Omogbai et al., 2005). By reducing RFOs (gas forming substrates), extended fermentations can improve gastrointestinal tolerance and are expected to modestly lower postprandial glycemic excursions by replacing fermentable oligosaccharides with organic acids and biomass, although the net glycemic effect ultimately depends on formulation and residual sugars (Kim et al., 2019). Fat composition and fatty acid profile. Lipid changes with time are subtler but detectable. In time resolved comparisons, yeast assisted or LAB fermentations of soymilk showed small shifts toward higher unsaturated:saturated ratios after ~24–48 h, alongside decreases in specific fatty acids (e.g., palmitic) and modest remodeling of linoleic/oleic proportions effects attributed to limited lipase activity and microbial utilization of certain fatty acids during prolonged fermentation (Mehaya et al., 2023). Where co cultures or specific strains are used, longer holding times may accentuate these trends, but very extended fermentations risk oxidative changes that can negatively affect flavor (Mehaya et al., 2023; Li et al., 2024).

Mineral bioavailability (phytate and oxalate over time). Phytate (and to a lesser extent oxalate) chelates divalent cations and limits absorption. LAB can express phytase or induce endogenous phytase activity; thus, as fermentation time increases, phytic acid is hydrolyzed and mineral bioaccessibility improves. Controlled fermentations of soy beverages with different LAB consortia show time dependent decreases in phytic acid and concomitant rises in dialyzable Ca, Zn, and Fe, with the most pronounced gains after longer incubations (≥ 12 –24 h), particularly when phytase competent strains are included (Gan et al., 2023). A 2024 review synthesizing plant based fermentations confirms that extended or strain selected fermentations enhance mineral bioavailability by more complete phytate degradation (Samtiya et al., 2024).

Vitamin dynamics (B vitamin synthesis and loss). B group vitamins can increase during fermentation as certain LAB synthesize riboflavin and folates; these changes generally scale with time until cell growth slows. Recent work targeting riboflavin producing *Lactiplantibacillus plantarum* in soymilk demonstrates time responsive enrichment of B2 during fermentation, although a fraction remains cell associated and may require cell disruption or longer maturation to maximize release (Rana et al., 2025). Conversely, protracted fermentations can degrade oxygen sensitive vitamins; therefore, there is often a time “sweet spot” (roughly a day) where synthesis exceeds loss (Kim et al., 2019; Rana et

al., 2025). Notably, vitamin B12 does not reliably accumulate without B12 producing adjuncts; earlier mechanistic studies show that specialized cultures are required, and time alone in standard LAB fermentations is insufficient (Molina et al., 2012).

Bioactive compounds (isoflavone aglycones). One of the clearest time linked transformations is the β glucosidase-mediated conversion of isoflavone glucosides (e.g., genistin, daidzin) to more bioavailable aglycones (genistein, daidzein). Multiple studies report significant aglycone accumulation between ~24 and 48 h, tracking enzyme activity and cell density; beyond that window, gains may plateau (Mehaya et al., 2023). Broader chemical profiling confirms that extended fermentation enhances aglycone proportion, increases total phenolic content, and strengthens antioxidant readouts, with magnitude dependent on the inoculum and holding time (Hwang et al., 2021; El Shazly et al., 2021). Emerging work now optimizes fermentation duration explicitly to maximize aglycone yield, underscoring time as a primary lever (Zheng et al., 2025).

Putting the kinetics together. In practical terms, the first 8–12 h primarily deliver acidification and early RFO use; ~12–24 h sees robust proteolysis, phytate hydrolysis, and rising aglycones; ~24–48 h tends to maximize many desirable endpoints (aglycones, certain peptides, mineral bioaccessibility), after which returns diminish and risks of vitamin loss or off flavors increase. Therefore, “optimal” time is strain and target dependent: formulations prioritizing aglycones and mineral bioaccess may benefit from the longer end of this window, while those emphasizing delicate flavor or vitamin retention may choose shorter fermentations (Kim et al., 2019; Gan et al., 2023; Mehaya et al., 2023).

Role of Microbial Activity and Fermentation Kinetics

In soy based yoghurt systems, who the microbes are and how fast they move through growth phases jointly determine the nutritional trajectory as fermentation time increases. Classic yoghurt starters *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* exhibit well characterized proto cooperation: *S. thermophilus* rapidly acidifies and liberates amino acids that stimulate *L. delbrueckii*, while the latter contributes proteolysis and additional acidification; kinetic models show that lactic acid production is largely growth associated and can be predicted from phase transitions under pH control. Although those dynamics were first quantified in dairy media, the same kinetic principles (lag →

exponential → stationary) govern plant matrices and can be adapted to soy, with time dependent links between biomass, acidification, and metabolite formation.

When these dairy starters are applied to soymilk, their behavior diverges from milk due to the different sugar spectrum (sucrose and raffinose family oligosaccharides rather than lactose) and the presence of soybean anti nutritional factors. Controlled trials have demonstrated that commercial yoghurt cultures can indeed produce stable “yoghurt type” fermented soy beverages, but with distinct acidification and texture kinetics compared with dairy, underscoring that fermentation time windows optimized for milk are not directly transferable to soy. Co culturing with probiotic adjuncts (e.g., *Lactiplantibacillus plantarum*, *Lacticaseibacillus casei*) is commonly used to tailor kinetics toward improved nutrient transformations within practical processing times.

Across growth phases, specific metabolic activities map onto nutritional changes as time advances. During early exponential growth, carbohydrate catabolism drives pH decline; mid to late exponential phases upregulate β glucosidase, accelerating conversion of isoflavone glucosides (genistin, daidzin) to more bioavailable aglycones (genistein, daidzein). Time course fermentations show substantial aglycone accumulation within hours to a day often peaking between ~24–48 h depending on strain and temperature after which gains plateau in stationary phase. This kinetic linkage between cell density, enzyme expression, and isoflavone bioconversion is one of the clearest ways fermentation time reshapes soy bioactives.

Simultaneously, proteolysis and peptidolysis proceed as cell wall and extracellular proteases become active; extended fermentations increase low molecular weight peptides and free amino acids that are more digestible and may confer antioxidant activity. Recent soy yoghurt evaluations and strain screens report higher peptide release and improved in vitro protein digestibility once cultures traverse into late exponential/early stationary phases, though the magnitude is strain and time dependent. Over extension beyond the optimal window yields diminishing returns as proteolysis plateaus with slowing growth.

For mineral bioavailability, time favors improvement. Lactic acid bacteria can express phytase and/or activate endogenous phytases as pH drops, resulting in progressive phytic acid hydrolysis and increased dialyzable Ca, Zn, and Fe with longer fermentation (≥ 12 –24 h). Studies in fermented soy beverages confirm time dependent phytate

degradation and mineral release, especially when phytase competent strains are used or when fermentation proceeds long enough to sustain enzyme action into stationary phase.

Vitamins respond bidirectionally to time. Certain LAB synthesize B vitamins (e.g., riboflavin, folates), and riboflavin overproducing mutants have been used to bio enrich fermented soy beverages during standard fermentation windows. However, protracted incubations can risk oxidative or metabolic losses of sensitive vitamins; thus, vitamin outcomes reflect a balance between microbial synthesis during exponential growth and potential degradation later, reinforcing that the “right” time depends on the target micronutrient profile.

Kinetic modeling and community scale simulations help explain why a fixed fermentation time rarely suits all endpoints. Genome scale and dynamic models of yoghurt consortia predict that metabolite cross feeding (amino acids, formate, peptides) and acid stress thresholds shift the system from growth coupled synthesis (e.g., B vitamins, peptides) to maintenance states where additional time contributes little nutritionally and may harm texture or flavor. Accordingly, optimizing for aglycones and mineral bioaccess may justify longer holds, whereas preserving certain vitamins or minimizing over acidification favors shorter, strain specific schedules.

Finally, strain choice steers how time translates into nutrition. In soy media, *S. thermophilus* and *L. delbrueckii* can be paired with β glucosidase or phytase active probiotics (*L. plantarum*, *L. fermentum*, *L. acidophilus*, *L. casei*) to accelerate desired transformations within commercially reasonable times. Recent compositional studies of soy yoghurt fermented with different starters show that selecting strains with the right enzyme repertoire allows shorter fermentations to reach the same nutritional endpoints that would otherwise require longer holds mitigating risks of vitamin loss or excessive acidification.

In practical terms, time is a lever whose effect is gated by kinetics: early time primarily acidifies and starts isoflavone hydrolysis; mid time ($\approx 12\text{--}24$ h) maximizes proteolysis, aglycones, and phytate breakdown; late time ($>24\text{--}36$ h) often yields smaller nutritional gains while increasing the likelihood of over acidification, texture defects, or vitamin decline. Selecting strains and setting fermentation duration with these kinetic constraints in mind is therefore central to delivering nutritionally optimized soybean based yoghurt.

Optimal Fermentation Time from Literature

Across the soy yoghurt literature, “optimal time” is not a single number but a window that depends on the intended nutritional target, the starter set, and processing parameters. Still, patterns emerge when studies are grouped into short ($\approx 4\text{--}8$ h), medium ($\approx 8\text{--}24$ h), and long ($\geq 24\text{--}48$ h) fermentations.

Short fermentations ($\approx 4\text{--}8$ h).

Within the first 4–8 hours, lactic cultures rapidly acidify soymilk and begin early enzymatic transformations with modest yet meaningful nutritional effects. Time resolved mineral bioavailability studies show that calcium absorption from *Lactocaseibacillus*/*Lactiplantibacillus* fermented soy beverages rises detectably by 4 h and improves further by 8–12 h, indicating that phytate hydrolysis and/or complex dissolution begins early in the run (often with *L. plantarum*) (Gan et al., 2023). In the same study, total dialyzable minerals increased progressively with fermentation time, peaking near 12 h depending on the strain (Gan et al., 2023). From a carbohydrate perspective, short fermentations initiate α galactosidase driven use of raffinose family oligosaccharides (RFOs), easing gastrointestinal tolerance even before extensive proteolysis occurs; this dynamic is well documented in LAB fermented soymilks and related systems (Wang et al., 2003). Probiotic viability also climbs quickly during the first 8 h as exponential growth proceeds, though the exact counts depend on inoculum and sugar profile (Kim et al., 2019). In sum, short holds are useful when the goal is to secure high viable counts and kick start phytate reduction and isoflavone bioconversion without heavy flavor/texture change.

Medium fermentations ($\approx 8\text{--}24$ h).

Between 8 and 24 hours, most studies report peak or near peak improvements in several nutritional endpoints. First, phytase activity in LAB fermented soymilk often surges between 12 and 24 h (with pH ≈ 5), driving marked declines in phytic acid and higher bioaccessibility of Ca, Fe, and Zn (Tang et al., 2010; Gan et al., 2023). Second, β glucosidase expressed by many LAB strains converts isoflavone glycosides (daidzin, genistin) to more bioavailable aglycones (daidzein, genistein), with several time course studies showing substantial aglycone accumulation by 24 h (Hwang et al., 2021; Madjirebaye et al., 2022). Third, proteolysis and peptidolysis intensify: peptide and free amino acid pools rise, in vitro protein digestibility improves, and antioxidant peptide signals

strengthen, outcomes repeatedly observed in fermented soy matrices as the culture transitions from late exponential to early stationary phase (Ketnawa et al., 2021; Mehaya et al., 2023). Fourth, certain B vitamins can be synthesized during this window riboflavin enrichment is demonstrable when riboflavin overproducing LAB are used; synthesis appears to scale with growth and time, up to a point (Langa et al., 2024; Thakur et al., 2016). Collectively, these kinetics explain why many formulations select ~12–24 h as a compromise that maximizes bioactives and mineral bioaccess while maintaining good viability and acceptable flavor/texture.

Long fermentations (≥ 24 –48 h or more).

Extending the run into 24–48 h can further increase some targets but at a diminishing returns rate and with trade offs. For isoflavones, aglycone proportions often continue rising into the second day before plateauing (Hwang et al., 2021). Recent optimization work designed specifically to time the aglycone peak confirms that ~24–48 h is a typical maximum for high conversion strains (Zheng et al., 2025). Likewise, long fermentations can push proteolysis and small peptide release higher and may modestly remodel fatty acid profiles, although the latter effects are generally small and strain dependent (Mehaya et al., 2023). On the other hand, prolonged holds risk vitamin losses (depending on oxygen exposure/temperature), sensory acidification, and texture defects; viability can also decline as cells enter stationary/maintenance states (Mani López et al., 2014; Ziarno et al., 2023). Therefore, “going long” is best justified when maximizing aglycones, selected peptides, or deeper phytate hydrolysis outweighs potential penalties; otherwise, medium times are nutritionally efficient.

Putting the time windows together.

Synthesizing across studies, a practical mapping emerges: 4–8 h primarily secures rapid growth/acidification, initiates RFO reduction, and begins mineral bioaccess gains; 8–24 h typically maximizes improvements in mineral bioavailability, isoflavone aglycones, and peptide linked digestibility while sustaining high probiotic counts; ≥ 24 –48 h may incrementally lift aglycones/peptides further but with rising risks of vitamin depletion, over acidification, and viability decline (Gan et al., 2023; Tang et al., 2010; Hwang et al., 2021; Mehaya et al., 2023; Mani López et al., 2014). Importantly, strain choice can compress these timelines: phytase or β glucosidase strong strains (e.g., *L. plantarum* variants) can achieve medium window outcomes in shorter runs, whereas dairy starters alone may

require longer times in soy to reach similar endpoints (Ziarno et al., 2023; Langa et al., 2024).

Health Implications

Protein digestibility and allergenicity.

Improvements in digestibility that accompany longer fermentation (to a point) have potential relevance for protein utilization and tolerance. Controlled comparisons indicate that fermentation steps increase in vitro digestibility and liberate indispensable amino acids relative to unfermented or merely heated soy matrices (Ketnawa et al., 2021). Parallel lines of evidence suggest that fermenting reduces immunoreactivity of major soy allergens β conglycinin (7S) and glycinin (11S) through proteolysis and conformational change, though outcomes depend on strain, pH, and time. For example, *Enterococcus faecalis* VB43 fermentation reduced antigenicity of 7S/11S in soymilk, and several LAB, including *Lactiplantibacillus plantarum*, have shown IgE reactivity decreases in model systems; these effects are generally greater with extended fermentation within a technologically reasonable window (Biscola et al., 2017; Liu et al., 2021; Liu et al., 2023). Reviews of soy allergenicity corroborate that fermentation is among the most promising mitigation strategies, while also calling for more human data to quantify clinical benefit (Wiederstein et al., 2023).

Probiotic counts and gut health relevance.

Health effects of fermented foods often hinge on delivering adequate live cells (typically $\geq 10^6$ – 10^7 CFU/mL at consumption). In soy beverages, viable LAB counts commonly rise to 10^7 – 10^8 CFU/mL during standard fermentation windows (≈ 6 – 24 h), then are maintained or slowly decline during refrigerated storage; retention is strain and matrix dependent (Mehaya et al., 2023; Ziarno et al., 2023). Classic dairy evidence shows that even with some decline over storage, several probiotic yogurts maintain $\geq 10^7$ CFU/mL for weeks, a useful benchmark for soy systems pursuing comparable claims (Mani López et al., 2014). More recently, synbiotic strategies (e.g., immobilizing *Lactocaseibacillus rhamnosus* on okara fiber) achieved large gains in viability over a 12 h fermentation and improved acid/organic acid profiles, illustrating that strain selection plus time optimization can jointly maximize probiotic delivery (Gad et al., 2024). Because LAB viability typically peaks around the end of exponential growth, medium fermentation times (~ 8 – 24 h) tend to best balance high CFU with desirable nutrition and flavor; very long

fermentations risk viability loss and sensory penalties that could reduce intake (Ziarno et al., 2023; Mani López et al., 2014).

Micronutrient status: minerals and vitamins.

Time dependent phytate degradation improves the bioaccessibility of divalent minerals, a mechanistic link that underpins potential benefits for iron and zinc status when soy products are consumed habitually. In fermented soy beverages, mineral absorption proxies increased from 4 h to 12 h and were highest around the latter, consistent with rising phytase action and acidification (Gan et al., 2023). For vitamins, a balanced view is needed: medium times support riboflavin/folate biosynthesis by selected LAB (a benefit), while extended times and oxygen exposure can degrade labile vitamins (a risk) (Langa et al., 2024; Thakur et al., 2016). Thus, in population health terms, a mid range fermentation that secures mineral bioaccess and vitamin gains without over maturation appears most defensible.

Bioactives and metabolic endpoints.

Soy isoflavone aglycones more readily absorbed than their glycoside precursors rise with fermentation time, often peaking around 24–48 h; these kinetics suggest potential for improved systemic exposure to genistein/daidzein and related antioxidant effects (Hwang et al., 2021; Madjirebaye et al., 2022; Zheng et al., 2025). Beyond isoflavones, metabolomics of extended soymilk fermentations show increases in peptides and amino acid derivatives and later rises in lipid/flavonoid metabolites, though extremely long runs (>48–84 h) are industrially uncommon and can compromise palatability (Gao et al., 2022). Consequently, medium to long times can be justified when the product targets bioactive enrichment provided sensory and vitamin stability are preserved.

Suitability for lactose intolerant and vegan consumers.

Soy yoghurt is inherently lactose free and suitable for vegan diets; optimizing fermentation time does not change this identity but can influence tolerability and appeal. By depleting RFOs and reducing “beany” volatiles, appropriate time windows improve gastrointestinal comfort and flavor acceptance (Wang et al., 2003; Huo et al., 2023). For lactose intolerant consumers seeking probiotic benefits comparable to dairy yoghurt, time tuned soy fermentations that maintain $\geq 10^7$ CFU/mL at point of consumption are a plausible alternative (Ziarno et al., 2023; Mani López et al., 2014).

Bottom line for practice and policy.

From a health optimization standpoint, medium fermentation times (~8–24 h) most consistently deliver: (i) improved protein digestibility with reduced allergenic potential; (ii) strong probiotic viability; (iii) higher mineral bioaccess via phytate loss; (iv) measurable increases in bioactive aglycones; and (v) opportunities for B vitamin enrichment using appropriate strains. Longer times (24–48 h) can further enhance aglycones/peptides but must be weighed against potential vitamin attrition, over acidification, and declining CFU, whereas short times (4–8 h) are best when the priority is high cell counts with minimal sensory change. These conclusions align with kinetic evidence and strain specific findings across recent peer reviewed work in soy and related fermented systems.

Current Gaps and Future Directions

Despite growing research on soybean based yoghurt, significant gaps remain regarding the influence of fermentation time on nutritional quality. One major limitation is the scarcity of long term storage studies evaluating nutrient stability, probiotic survival, and sensory characteristics beyond the initial post fermentation period (Ziarno et al., 2023). Additionally, there is no universally accepted standardized fermentation protocol for soy based yoghurts, leading to wide variation in starter cultures, incubation conditions, and fermentation durations used across studies (Langa et al., 2024).

Another underexplored area is fortification research aimed at compensating for nutrient losses or tailoring products for specific health outcomes. While fortification with calcium, vitamin B12, and omega 3 fatty acids is common in plant based milks, systematic evaluation of such strategies in fermented soy products remains limited (Tang et al., 2010; Thakur et al., 2016).

Future research should also explore technological innovations to improve fermentation efficiency and nutritional retention. These may include enzyme assisted fermentation, use of immobilized probiotics, and novel microbial consortia with enhanced β glucosidase or phytase activities (Gad et al., 2024; Zheng et al., 2025). Metabolomics and proteomics approaches could provide deeper insight into nutrient transformation kinetics, supporting the development of predictive models for optimal fermentation time. Moreover, strain engineering and selection for targeted nutrient synthesis, such as folate or

riboflavin production, could expand the functional profile of soy yoghurts while addressing population specific nutrient deficiencies.

Conclusion

Fermentation time is a pivotal determinant of the nutritional and functional quality of soybean based yoghurt. Short fermentation times (4–8 hours) primarily ensure rapid acidification, initial reduction of anti nutritional factors, and high probiotic viability, but yield moderate nutrient transformation. Medium durations (8–24 hours) generally represent the optimal balance, maximizing protein digestibility, bioactive peptide release, mineral bioavailability, isoflavone aglycone content, and probiotic counts without compromising sensory quality. Extended fermentation (>24 hours) can further enhance certain bioactive compounds but may reduce vitamin stability, probiotic viability, and consumer acceptability.

From both consumer and industry perspectives, medium fermentation periods appear most favorable for producing nutritionally enhanced, palatable, and functionally beneficial soy yoghurts. However, industry wide adoption of optimized protocols will require further standardization, technological innovation, and long term stability data. Continued research in these areas will help to fully realize the health potential of soybean based yoghurt and strengthen its position within the expanding market for plant based functional foods.

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