


Review

Calcium-fortified foods in public health programs: considerations for implementation

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Low calcium intake is common worldwide and can result in nutritional rickets in children and osteomalacia in adults. Calcium-fortified foods could improve calcium intake. However, there is limited calcium fortification experience, with technical and practical issues that may hamper its adoption. The objective of this landscape review is to summarize these issues to help policymakers guide the planning and design of calcium fortification as a public health strategy. One challenge is the low bioavailability of calcium salts (~20–40%); thus, large amounts need to be added to food to have a meaningful impact. Solubility is important when fortifying liquids and acidic foods. Calcium salts could change the flavor, color, and appearance of the food and may account for 70–90% of the total fortification cost. Safety is key to avoid exceeding the recommended intake; so the amount of added calcium should be based on the target calcium intake and the gap between inadequate and adequate levels. Monitoring includes the quality of the fortified food and population calcium intake using dietary assessment methods. Calcium fortification should follow regulations, implemented in an intersectorial way, and be informed by the right to health and equity. This information may help guide and plan this public health strategy.

Keywords: calcium; fortification; program; implementation

Introduction

Very low calcium intake is common in low-income settings,^{1,2} which can result in rickets in children and osteomalacia in adults and an increased risk of osteoporosis.³ It is also associated with other adverse health conditions, including preeclampsia and hypertension.^{3,4} Calcium supplementation trials before and during pregnancy have shown a reduction in the incidence and severity of preeclampsia.^{5–7} Based on these trials, the World Health Organization (WHO) recommends calcium supplementation in pregnancy, particularly in set-

tings of low calcium intake.⁸ However, there are major barriers to scaling-up the adoption of this WHO recommendation, such as calcium pill burden, high cost, low adherence, complex supply chains, side effects, and the nonuse of health services. Also, fortifying foods with calcium for women in pregnancy or prepregnancy⁹ does not benefit other segments of the population that may also need to improve calcium intake. Therefore, the discussion has changed to the option of fortification of staple foods with calcium as an effective means to help achieve adequate levels of calcium intake.

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Calcium fortification could reach remote populations or populations that lack contact with the health systems.

Calcium intakes below 600 mg/day have been reported in national surveys from Argentina, Bangladesh, Brazil, Bolivia, Cambodia, China, Indonesia, Japan, Kenya, Malaysia, Pakistan, the Philippines, Thailand, and Turkey.¹ It has been estimated that an additional 400–500 mg/day of calcium may be needed in these countries,² an amount feasible to be included in a food fortification strategy. However, there are only a few experiences with national food fortification of calcium worldwide,¹ such as the mandatory calcium fortification of wheat flour in the United Kingdom since 1943.¹⁰ Although this program has been successful in improving calcium intake in the British population,^{11,12} it is usually not mentioned in reviews on food fortification. The limited awareness on the prevalence of low calcium intake, along with little pressure from the population, thwarts the efforts toward including calcium-fortified foods in public health strategies. Also, there are challenges related to technology, feasibility, acceptability, and safety of a fortification of foods with calcium that may hamper its adoption, which may need additional research.

This landscape review aims to explore and synthesize the practical considerations for the planning and design of fortifying foods with calcium as a public health strategy to improve calcium intake. It is structured in the following five sections: (1) technical issues related to the calcium salts available for food fortification; (2) estimation of the safe, efficacious, and feasible amount of calcium to add to foods; (3) factors related to the selection of the food vehicle; (4) monitoring and evaluation of calcium-fortified foods; and (5) ethical aspects related to calcium-fortified foods. This review could be used as a guide when implementing this public health measure in settings with low calcium intake. A detailed description of the success of foods fortified with calcium worldwide can be found elsewhere.¹

A literature search was performed for each of the sections included in this landscape review. The information was identified through internet search engines and databases, such as Google, PubMed, Agricola, and CINAHL, using the following terms “fortification or fortificant,” “calcium or calcium salt,” and “foods and/or beverages.” Reports from

the WHO, Food Agriculture Organization, Institute of Medicine, Global Alliance for Improved Nutrition (GAIN), Micronutrient Initiative, Food Fortification Initiative, European Food Safety Authority, and CODEX were also reviewed as well as the references cited in many of the studies and reports. For additional information, experts in food fortification and calcium were contacted via e-mail, calls, and in-person meetings.

Physicochemical characteristics and cost of calcium salts used for the fortification of staple foods

There are different calcium salts approved to be used as food fortificants (e.g., calcium carbonate, calcium chloride, and calcium citrate; see Table 1).^{13–23} Most calcium salts used in food fortification for human consumption have a bioavailability ranging from 20% to 40%.²⁴ Their solubility, source, interaction with the food and/or with a whole meal, and bioavailability vary widely.

Calcium content of salts

There is great variability in the proportion of elemental calcium in different salts, ranging from as low as 7% for calcium gluconate to as high as 71% for calcium oxide (Table 1).

Bioavailability of salts

One of the most challenging technical issues in calcium food fortification is the low bioavailability of calcium from different sources, including calcium salts. Bioavailability is the amount of calcium that the body absorbs. This depends on several factors. For example, bioavailability is lower if calcium is consumed with an empty stomach compared with a light meal.²⁴ When a dose of 250 mg of elemental calcium is given with a meal, the absorption of calcium is 35% from malate citrate, 27% from calcium carbonate, and 25% from tricalcium phosphate.^{24–27} When comparing 11 different calcium salt combinations (single compound or combinations of salts), the bioavailability was 20–40%, which is within 10% of the bioavailability of calcium from milk (which is about 30%).²⁴ An exception is calcium citrate malate, which has been shown to have greater absorption compared with tricalcium phosphate/calcium lactate when 500 mg was added to orange juice among healthy premenopausal women.²⁸ This variability is probably reflecting the interaction with the food or

Table 1. Chemical properties of calcium salts, sources, and uses^{13,14,23,15–22}

Type of calcium ^a	Formula*	Percent bioavail-ability	Molecular weight	Solubility	Sensory properties	Source	Uses	Feasibility	Approved by
Calcium oxide (quick-lime)	CaO	71	56	Soluble in water, forming calcium hydroxide; soluble in acids, glycerol, and sugar solution; practically insoluble in alcohol. 23.3 mmol/L	Colorless, cubic, white crystals; odorless; slightly bitter taste	From heating limestone, coral, seashells, or chalk, which are mainly CaCO ₃ , to drive off carbon dioxide. Mainly calcium carbonate	Used as a nutrient and/or dietary supplement in animal drugs, feeds, clarification of cane and beet sugar juices	Readily absorbs oxygen and water from the air. May be difficult to use directly—immediately absorbs water after soil application	U.S. FDA
Calcium hydroxide (slaked lime)	Ca(OH) ₂	54	74	Soluble in boiling water, acid, glycerol, sugar, or ammonium chloride solution and insoluble in alcohol. 25 mmol/L	Hexagonal crystals or soft granules or powder; odorless; slightly bitter alkaline taste	Formed when water is added to calcium oxide	Used as calcium salts, causticizing soda, purification of sugar juices, food additive as buffer and neutralizing agent, shell-forming agent (poultry)		U.S. FDA/ EFSA
Calcium silicate	Ca ₂ O ₄ Si	50	116	Insoluble in water	White or creamy colored, free-floating powder	Occurs naturally in wollastonite as calcium metasilicate; combination of calcium ions (from limestone, dolomite, etc.) and silicate ions (from silica)	Used as an indirect food additive; as an anticaking agent in animal feed; and as solid diluent	Tolerance 2% and 5%	U.S. FDA
Calcium carbonate ^b	CaCO ₃	40	100	Insoluble in alcohol, practically insoluble in water; soluble in dilute acids. 0.153 mmol/L	White hexagonal/orthorhombic crystals or powder (calcite; aragonite; vaterite); odorless; colorless; chalky, soapy, or lemony taste	Rock-derived (marble and limestone) and from eggshell and fishbone	Used as a direct food additive and nutrient supplement, as a dough strengthener, firming agent, pH control agent, stabilizer, and thickener		U.S. FDA/ EFSA
Hydroxyapatite	Ca ₅ (PO ₄) ₃ (OH)	40	502	0.08 mmol/L	–	–	–	Highly stable	–
Calcium phosphate tribasic	Ca ₃ (PO ₄) ₂	38	310	Insoluble in alcohol and acetic acid, and soluble in dilute hydrochloric acid and nitric acid. Slightly soluble in water. 0.064 mmol/L	White amorphous, or crystalline powder; odorless; sandy or bland taste.	Rock-derived, as oxyapatite, voelicherite, and whitlockite. Manufactured from phosphate rock, silica, wet-process phosphoric acid, and soda ash. Also found in cow's milk	Used as a supplement in livestock and poultry feeds; as food additives to control the pH in doughs and lard, as a yeast nutrient in flour		U.S. FDA
Calcium chloride	CaCl ₂	36	111	Extremely soluble in water. 6712 mmol/L	White cubic crystals or powder; colorless; odorless; taste threshold in potable water is 150–350 ppm. Salty, bitter taste	Isolated from brine	Used for melting ice and snow, and as a dust suppressant		U.S. FDA/ EFSA

Continued

Table 1. Continued

Type of calcium ^a	Formula*	Percent bioavail-ability	Molecular weight	Solubility	Sensory properties	Source	Uses	Feasibility	Approved by
Calcium formate	Ca(HCOO) ₂	31	130	Soluble in water	Orthorhombic crystals or crystalline powder; white or pale yellow; slight acetic acid-like odor	Manufactured from Ca(OH) ₂ and CO at high temperature and pressure	Used as a preservative for silage, food; for animal feed		
Calcium phosphate dibasic	CaHPO ₄	30	136	Soluble in hydrochloric acid, nitric acid, acetic acid, and ammonium citrate solution. Insoluble in ethanol. 1.84 mmol/L	White powder or crystalline solid; sandy or bland taste; odorless	Made from calcium carbonate and phosphoric acid	Used in powdered drink mixes (buffering agent), effervescent tablets, antacids, baking products (leavening agent), animal feeds, and mineral supplements	Nonhygroscopic, relatively stable material. Should be stored in a well-closed container in a dry place	U.S. FDA/EFSA/Health Canada
Calcium sulfate	CaSO ₄	29	136	Soluble in water. 15.3 mmol/L	Natural anhydrite crystals orthorhombic, color varies (white, blue, gray, or reddish tinge); odorless; tasteless	Made from calcium chloride and sol sulfate	Used in making tofu and water treatment	Store in a well-closed container	U.S. FDA
Calcium acetate	C ₄ H ₆ O ₄ Ca	25	158	Soluble in water; slightly soluble in alcohol; needles, granules, or powder form. 2364 mmol/L	Brown, gray, or white powder, amorphous or crystalline; slight odor of acetic acid; bitter taste	Action of pyroigneous acid on calcium hydroxide	Used as a food stabilizer and thickener for gelatins and puddings; as an antifoam additive; as an antimold agent in bakery goods; and as a firming agent for potatoes	Decomposes on heating; very hygroscopic; needs to be stored tightly	U.S. FDA
Calcium malate	C ₄ H ₄ CaO ₅	23	172	Slightly soluble in water	White powder	–	Used as an acidity regulator and flavor enhancer		
Calcium glycinate	C ₄ H ₈ CaN ₂ O ₄	21	188	Soluble in water			Used as a dietary supplement		
Tricalcium citrate	Ca ₃ (C ₆ H ₅ O ₇) ₂	21	498	More soluble at low temperatures (advantage for cold and hot food processing). 2.006 mmol/L	White powder; odorless; neutral tasting	A by-product in the manufacture of citric acid	In the production of citric acid and other citrates; improvement of baking properties of flour; as a dietary supplement; as a sequestrant, buffer, and firming agent in foods		
Calcium citrate	Ca ₃ (C ₆ H ₅ O ₇) ₂	21–24	498	Insoluble in alcohol, soluble in 1050 parts cold water; somewhat more soluble in hot water; tetrahydrate. 1.49 mmol/L	Colorless or white powder, odorless; tart, acidic taste	Rock-derived. Calcium sourced from marble or limestone bound with citric acid	Used as a general-purpose food additive, as a nutrient and/or dietary supplement, and as a sequestrant		U.S. FDA/EFSA
Calcium citrate malate	(C ₆ H ₇ O ₇) _x ·(C ₄ H ₅ O ₅) _y ·(Ca ₂ ⁺) _z	21–24	671	Soluble in water. 80 mmol/L	Colorless or white; odorless	Rock-derived. Calcium sourced from marble or limestone bound with citric acid and malic acid	Used as a general-purpose food additive, as a nutrient and/or dietary supplement, and as a sequestrant		U.S. FDA/EFSA

Continued

Table 1. Continued

Type of calcium ^a	Formula*	Percent bioavailability	Molecular weight	Solubility	Sensory properties	Source	Uses	Feasibility	Approved by
Calcium lactate	C ₆ H ₁₀ CaO ₆	13–18	218	0.13 mmol/L	White, neutral taste, almost odorless. Unpleasant taste if too concentrated	Rock-derived. Calcium sourced from marble or limestone bound with lactic acid. Also found in foods like aged cheese	Preservative in foods and beverages; calcium replenisher		U.S. FDA/EFSA
Calcium lactate gluconate	C ₉ H ₁₆ CaO ₁₀	12	324	Highly soluble. 1233 mmol/L	White, crystalline, odorless, tasteless powder	Mixture of calcium gluconate and calcium lactate	Used for clear beverages and concentrated or instant preparations (baby food, infant formula, dairy, desserts, jams, and soy products), also as a pH adjuster and chelating agent	Powder; store in airtight plastic container at room temperature or refrigerator; easy to process; highly stable against phenols, tartrates, and CO ₂	U.S. FDA/EFSA
Calcium ascorbate	CaC ₁₂ H ₁₄ O ₁₂	10	390	Freely soluble in water; practically insoluble in methanol and ethanol	A white to slightly yellow crystalline powder; odorless	Rock-derived. Calcium sourced from marble or limestone bound with ascorbic acid	Antioxidant/color fixative (prepared meat, dairy, and baby products)		U.S. FDA
Calcium glycerol-phosphate	C ₃ H ₇ CaO ₆ P	10	210	1 g in 50 mL of water at a lower temperature; insoluble in alcohol. 95.2 mmol/L	Fine, white, odorless, almost tasteless powder	Glycerophosphoric acid	Used as a dietary supplement; and in food products such as gelatins, puddings, and fillings	Hygroscopic	U.S. FDA/EFSA
Calcium gluconate	C ₁₂ H ₂₂ CaO ₁₄	9	430	Slowly soluble in water; insoluble in organic solvents. 73.6 mmol/L	Crystals, granules, or powder; white, bland taste or tasteless, odorless	Rock-derived. Calcium sourced from marble or limestone bound with gluconic acid	Used in coffee powders to prevent caking, as a sequestering agent; food additive; as buffer; in vitamin tablets; a gelling agent in foods; sequestrant in foods	Stable in air. Loses water at 120 °C. Store below 40 °C. Protect from freezing	U.S. FDA/EFSA
Calcium glubionate	C ₁₈ H ₃₄ CaO ₂₀	7	611	Soluble in water, freely soluble in boiling water. 95.2 mmol/L	White to yellow-tinged white crystalline powder; almost tasteless, odorless		Used as a dietary supplement	Store in a well-closed container at a temperature not exceeding 25 °C, protected from direct sunlight and moisture	
Calcium stearate	C ₃₆ H ₇₀ CaO ₄	7	607	Slightly soluble in hot vegetable and mineral oils; quite soluble in hot pyridine; insoluble in alcohol and ether. 0.0007 mmol/L	Fine, crystalline white to yellowish white bulky powder	Made from calcium chloride and sodium salts of mixed fatty acids (stearic and palmitic)	Used as a food additive; as conditioning agent; as an anticaking agent in dehydrated vegetable products, salt, and onion and garlic powder; to ensure tablet supplements do not stick in the machine	Decomposed by many acids and alkalis; when heated to decomposition, it emits acrid smoke and irritating fumes	U.S. FDA

Continued

Table 1. Continued

Type of calcium ^a	Formula*	Percent bioavail-ability	Molecular weight	Solubility	Sensory properties	Source	Uses	Feasibility	Approved by
Calcium propionate	C ₆ H ₁₀ CaO ₄	NA	186	Soluble in water; slightly soluble in methanol and ethanol; practically insoluble in acetone and benzene	Powder or monoclinic crystals; white or colorless	Made from propionic acid + calcium hydroxide	Inhibitor of molds and other microorganisms in bread and other foods; for encapsulation in hydrogenated vegetable oil; in chemically leavened products	When heated to decomposition, it emits acrid smoke and irritating fumes	U.S. FDA
Calcium peroxide	CaO ₂	NA	72	Slightly soluble in water; soluble in acids with formation of hydrogen peroxide	White or yellowish powder; white tetragonal crystals; odorless; almost tasteless	Made by the interaction of solution of a calcium salt and sodium peroxide with subsequent crystallization	Used in chewing gum; as dough conditioner in the United States but not in Europe; for cultivation of tomatoes, cucumbers, tobacco, and prawns in Japan; as a coating on beet seeds in Europe	Hygroscopic; decomposes in moist air; need to store in well-closed container	U.S. FDA
Calcium caseinate	C ₈₁ H ₁₂₅ N ₂₂ O ₃₉	NA		Stable at a pH > 5.7. At a neutral or acidic pH, casein is relatively insoluble in water, and is easily separated from other milk proteins, sugars, and minerals. It is influenced by heat with temperatures as low as 50 °C (122 °F)	Appears as a milky liquid	Produced by changing the pH of milk to neutral or acid to become insoluble in water and isolate it from the other proteins in milk. It is then combined with calcium hydroxide at high alkaline levels and dries the protein	Used in the formation of emulsions in coffee whiteners, desserts, and whipped toppings; to produce sausage skins; to coat fruit and vegetable products for freshness	Very stable substance. It increases the shelf life, improves nutritional content, and enhances taste and smell	U.S. FDA
Calcium iodate	Ca(IO ₃) ₂	NA	390	Solubility in water: 0.10 g/100 mL. More soluble in aqueous solutions of iodides and amino acid solvent than in water	Monoclinic-prismatic crystals; colorless; odorless	Prepared by passing chlorine into a hot solution of lime in which iodine has been dissolved	Used to improve properties of yeast-leavened bakery products; nutritional source of iodine in foods and feedstuffs; as food additive, dough conditioner	Sensitive to reducing agents; decomposes on heating	U.S. FDA
Calcium pantothenate	C ₁₈ H ₃₂ CaN ₂ O ₁₀	NA	259	Very soluble in water, benzene, and ethyl ether	Yellow viscous oil	Calcium salt of the water-soluble vitamin B5	Skin conditioning agents	Unstable; easily destroyed by acids, bases, and heat. When heated to decomposition, it emits toxic vapors of nitric oxide	U.S. FDA

Continued

Table 1. Continued

Type of calcium ^a	Formula*	Percent bioavail-ability	Molecular weight	Solubility	Sensory properties	Source	Uses	Feasibility	Approved by
Calcium stearoyl-2-lactylate	C ₄₈ H ₈₆ CaO ₁₂	NA	895	Slightly soluble in hot water	White or slightly yellowish powder or brittle solid with a characteristic odor	Octadecanoic acid, 2-(1-carboxy-ethoxy)-1-methyl-2-oxoethyl ester, calcium salt (2:1)	As dough strengthener or emulsifier; as surface active agent, emulsifier, or stabilizer in icings, fillings, puddings, and toppings, in liquid and solid edible fat-water emulsion, snack dips, and cheese and cheese products, in sauces or gravies; as substitutes for milk and cream in coffee; as surface active agent in dehydrated potatoes		U.S. FDA

^a Elemental calcium absorbed in the body.

^b Calcium carbonate can come in various forms for use as dietary supplements, such as dolomite, bone meal, and oyster shell.

In terms of calcium equivalents, which can be calculated by the amount of the calcium salt (mg cation + mg anion, or mL of a specified concentration) or the amount of elemental calcium (in mg, mEq, or mmol), these salts vary a little.

*Calcium has a valence of +2, so mEq = 2 × mmol.

beverage vehicle. For example, calcium citrate malate added to fruit juices has greater absorption when added to apple juice compared with orange juice (tested in the same individuals) or when compared with the pure calcium salt in water.²⁴

One of the difficulties when fortifying with calcium is the large amount required to be added to a food vehicle to cover the population's calcium intake needs. A highly bioavailable calcium salt could be considered to avoid affecting the sensory properties of the food, although it does not change the amounts needed owing to the bulky nature of calcium.

Phytic²⁹ or oxalic acid^{30–32} reduces calcium bioavailability. To counteract this effect, certain types of enhancers can be added to the pre-mix. Hydrolyzed proteins and peptides can bind or chelate calcium and facilitate calcium absorption by preventing precipitation in the small intestine. One example is casein phosphopeptides. A study using calcium radioisotope showed that casein phosphopeptides significantly promoted calcium absorption.³³ There are several sources of hydrolyzed proteins and peptides, such as from

whey (germs and proteins), fish bones, krill, algae, and barley, among others.³⁴

Solubility of salts

In general, increasing solubility increases calcium absorption. Except for oxalate, most types of calcium salts have fairly good solubility. Citrate, malate, or bisglycino calcium have been shown to have very high solubility.³⁵

Solubility can be important, depending on the type of vehicle (liquid or solid). For example, for milk, fruit juices, and other beverages, solubility, dissolution characteristics, and stability of ingredients in solution are important to consider. In these beverages, the calcium salts can settle in the bottom of the container and even vigorous shaking is not enough to suspend the calcium salt.²⁴ In these vehicles, high-soluble calcium salts are preferred, such as calcium citrate, malate, lactate, or gluconate. However, the bioavailability of some of these salts can be low (9–13%). If the beverage is acidic, such as in orange juice, these salts are often used because the acidity of the fruit increases the solubility of the calcium salt and therefore, it may

increase bioavailability. However, the acidity can also cause problems of stability with calcium pantothenate. In other nonacidic foods, manufacturers often decrease the pH to improve solubility. Also, when using low soluble calcium salts, sequestering agents with pH adjustment are added to prevent sedimentation. Also, stabilizers such as carrageenan and guar gum are added. This is a common practice when fortifying milk, milk-based beverages, and products such as yogurt and cheese, to maintain calcium in suspension and to improve mouthfeel and appearance. For soy milk, stabilizers such as sodium hexametaphosphate or potassium citrate are used when they are fortified with calcium gluconate or lactogluconate.³⁶ Other calcium salts have higher bioavailability, but they may give a bitter or salty taste. Calcium carbonate has high bioavailability but low solubility. A good combination is tricalcium citrate, which has a high calcium level (21%) and moderate solubility (1 g/L). Tribasic calcium phosphate, calcium carbonate, and calcium lactate gluconate are used for milk, yogurt, and cheese, but the cross-linking between calcium with proteins, phosphates, and pectins may result in calcium sedimentation; therefore, chelating agents and stabilizers may be needed.^{16,37} Alternatively, calcium salts with high dispersion, such as tricalcium citrate, could be used to prevent this. Also, calcium salts could be combined, for example, by adding calcium citrate or organic acid. Calcium gluconate is soluble but may interact with other ingredients in the product and affect flavor.³⁸

Interaction with the food and/or with a whole meal

In terms of organoleptic changes, it is important to take into account flavor, the mouthfeel of the finished product, odor, and color. It is known that calcium fortification may increase acidity, chalkiness, bitterness, and change the flavor of the food through calcium or associated ions. To avoid these undesirable effects, manufacturers often use chelating agents (e.g., tripotassium citrate) or stabilizers (e.g., sodium hexametaphosphate, potassium citrate, and carrageenan).¹⁶

Calcium ions may affect flavor depending on the type of salt used, the food matrix, and the industrial process. Most calcium salts are bland, although calcium citrate has a tart flavor, calcium hydroxide is slightly bitter, and high concentrations of calcium

chloride and calcium lactate can be unpleasant. A study testing different calcium citrate malate levels added to orange juice found that the addition of up to 600 mg in 240 mL did not reduce consumers' acceptability, although it did make the beverage more astringent.³⁹ Also, calcium carbonate, dicalcium phosphate, tribasic calcium phosphate, and calcium sulfate can provide a chalky taste and have a gritty mouthfeel, particularly if added in high amounts.³⁹

Most salts are either white or colorless, so they do not change the color of the product.^{13,14,18,21} However, some insoluble calcium salts could lighten the food color. On the other hand, soluble salts may interact with other food components, such as tannins, to cause darkening. Also, calcium can interact with anthocyanins containing vicinal hydroxyl groups, causing a red-to-blue color change.⁴⁰

In terms of appearance, the addition of calcium to high protein beverages can destabilize the protein, with sedimentation at the bottom. Therefore, to avoid sedimentation and improve mouthfeel and appearance, soy lecithin is often used to coat calcium ions for calcium fortification of plant-based milk.⁴¹

Because of these sensory issues, a few studies have evaluated the acceptability of calcium added to foods. For example, a study tested the sensory properties of wheat-flour tortillas fortified with calcium lactate, carbonate, or citrate.⁴² The fortified tortillas contained 114 mg of calcium per 48 g of tortilla, which is about nine times higher than the calcium content of the nonfortified version. The fortification did not change the moisture or rollability of all tortillas. Appearance, texture, flavor, aftertaste, and overall acceptability were good in all tortillas, but participants preferred the fortified tortillas with calcium carbonate over the control tortillas. Willingness to purchase tortillas was similar among all types of tortillas. Addition of calcium citrate malate to orange juice (up to 600 mg in 240 mL) did not reduce consumers' acceptability, although it did influence the astringency of the beverage.³⁹

Other nontraditional, experimental sources of calcium

Other sources of calcium are being experimentally used by the food industry, such as eggshell. Eggshell is composed of inorganic salts (92%), mainly calcium carbonate (98%), magnesium

carbonate (0.8%), and tricalcium phosphate (0.8%).⁴³ In addition, the use of eggshells can contribute to the reduction of food waste. A study in Lithuania tested eggshell powder as a calcium fortificant for rye bread at different doses (from 2.5 to 12.5 grams).⁴⁴ They found a better appearance of the crust, the color of the crumb, flavor, and overall acceptability compared with the control bread, with the best quality shown for the bread containing 5.0 g of eggshell powder. Because the shell of one egg contains 2.07 ± 0.18 g of calcium, it is a very rich source. More studies assessing food matrix, sanitary quality, feasibility, cost-effectiveness, and bioavailability are required before eggshell powders can be used. Another study used tuna bone bio-calcium to fortify whole wheat crackers, reporting a good quality and sensory properties,⁴⁵ although the acceptability of this source of calcium has not been reported yet. Calcium derived from marine algae has also been tested *in vitro* and in animal studies as a potential calcium source for food fortification.^{46,47}

Potential interactions with other nutrients

The amount of calcium and the food vehicle to fortify should be carefully considered so that other key nutrients are not affected. Based on short-term studies, calcium supplements inhibit iron absorption by 28–55%;⁴⁸ however, long-term studies (6 months–4 years) showed no effect of calcium supplementation (500–1200 mg/day) on iron status in individuals of different ages and gender.^{49–57} Calcium supplementation may also decrease zinc absorption and balance in healthy women⁵⁸ and premature infants.⁵⁹ The long-term effect of these interactions should be studied further to confirm if they pose a detriment. As argued by Lawrence and Mark,⁶⁰ the evidence on food fortification should not be restricted to individual foods and how these affect health, as eating is part of a complex system that includes food, traditional cuisine, social/environmental/public health interventions, and nutrient intake patterns, among others.

Cost

The cost of calcium salts can vary widely. The start-up cost of food fortification is relatively inexpensive for the food industry. In general, the greatest recurrent cost in a food fortification program is the premix,⁶¹ accounting for 70–90% of the cost.^{62,63} This cost will vary if only fortifying with calcium

or if the food is already being fortified with other micronutrients and the cost involves just adding calcium to the preexisting premix. Among industrialized countries, these costs are generally absorbed in the price of the fortified food product. However, among lower-income countries, there is less margin to absorb fortification costs, even if relatively low, which is an important deterrent for the food industry to become involved in market-driven fortification. Among all calcium salts, calcium carbonate is the most often used by the industry as it has the lowest cost, usually less than that of flour.

Estimation of safe, efficacious, and feasible amounts of calcium to add to foods

When establishing the calcium fortification dose, safety is of paramount importance. This is measured as the percentage of the population exceeding the upper limit, which is the maximum daily intake unlikely to cause adverse health effects.

Setting the amount of calcium to fortify in foods

Before adding calcium to new foods or the fortification premix in an existing program, knowledge about usual calcium intakes in the target population is one of the first steps (Box 1).^{64,65} There should be a compromise between the acceptable prevalence of inadequate calcium intakes, the potentially adverse interactions of calcium with other nutrients (e.g., iron and zinc), the risk of exceeding the calcium upper limit for certain groups with usual high calcium intake, the adverse effects in taste, color, and odor of the calcium salt with the food vehicle/matrix if added at higher levels, and the cost of the fortificants. It is important to set a target for the prevalence of inadequacy, rather than a target mean intake.⁶⁵ Therefore, a suggested initial target is to aim for about 2.5% or 5% of intakes to fall below the average requirement in each population group.⁶⁶

Simulation software for setting the amount of calcium to fortify in foods

The WHO Intake Modeling, Assessment and Planning Program software program (IMAPP)^{67–69} is a user-friendly software that assists in the estimation of the amount of a fortificant that would have to be added to a food vehicle to reach the desired

Box 1. Steps in setting the amount of calcium to be added based on nutritional needs, calcium compound, and food vehicle^{64,65}

Step	Recommendation
Measuring food intakes	Data can be obtained from a national nutritional survey representative of different age groups and gender. It is recommended that data be collected as 24-h recalls or food records from at least 2 nonconsecutive days in different days of the week to calculate the individual variability. ^{101,102} The second recall can be done in a subset sample.
Calculating calcium intakes	Using data from the 24-h recalls, nutrient intakes need to be calculated, preferably from a nationally representative food composition database. If this is not available, regional food composition databases can be used.
Adjusting the distribution of calcium intakes	Using data from the two 24-h recalls, statistical adjustment is needed to adjust for within-individual nutrient intake variation to obtain usual nutrient intakes by age and gender. This can be done using the IMAPP, even if a second 24-h recall is not available, as it will estimate the variability using an external within-individual variability.
Assessing the prevalence of inadequate calcium intakes	This is done based on an established cut-point for each nutrient to calculate the prevalence of inadequate intakes based on the proportion of individuals with usual intakes below this level, for most nutrients.
Assessing the prevalence of potentially excessive calcium intakes	This can be calculated based on the proportion of individuals with intakes above the tolerable upper level.
Selecting the food vehicle to fortify with calcium	This step requires knowledge of the level of consumption of staple foods by age and gender. It also requires consideration of other nutrients being fortified in these staple foods to understand potential interactions and presence of certain substances that can interfere in calcium absorption, such as phytates and oxalates, as discussed before. Also, this vehicle must be consumed in enough quantity by the population at risk of deficiency and preferably not by the population with high intakes when there are concerns about excessive intakes.
Estimating the desirable calcium fortification levels	This can also be estimated using IMAPP. For this, a target median intake of calcium must be set in addition to the nutrient intake gap, which is based on a selected target prevalence of inadequacy (e.g., 2.5%, 20%, or other). This software will then calculate the different intake levels using different levels of fortification. The amount of calcium required to reposition the median to the target median intake equates to the amount of calcium needed to add to the food vehicle. The software will simulate the percent of the population that will still have inadequate intakes with the level chosen, by age and gender. It will also calculate the percent that would have excessive intakes. An acceptable percentage for excessive intake is 2–3%; if above this level, the level of calcium to be added should be reduced and the simulation should be rerun. However, some scenarios may not allow to achieve the target prevalence of inadequacy while ensuring an acceptably low prevalence of excessive intake.
Selecting the appropriate calcium salt	The type of calcium salt to use will depend on the food vehicle, the amount of calcium that is needed to close the gap, the bioavailability and stability of the calcium salt, the amount of competing substances (e.g., phytates and oxalates) in the food vehicle, other fortificants being currently added, and the sensory properties of the food vehicle.

Table 2. Simulation study for potential calcium fortification programs in Canada⁷²

Product	Level of calcium addition (mg) per serving	Total calcium intake would increase by (mg)		Proportion of population exceeding the recommendations (%)	
		Men	Women	Men	Women
Breads, cereals, and rice	55	83	48	2.27	0.10
Breads, cereals, and rice	165	427	289	6.29	0.21
Noncarbonated beverages	300	59	29	3.50	0.10
All types of beverages (including juices and carbonated beverages)	300	433	273	7.52	0.62

NOTE: Calcium recommendation in adults ranges from 1000 mg/day (adults 19–65 years and lactating females), 1200 mg/day (pregnancy), and 1300 mg/day (postmenopausal women and men 65+years).

prevalence of nutrient inadequacy. It is used as a simulator of different fortification scenarios to identify the best food vehicles to fortify and estimate how effective a fortification program will be. IMAPP is available to download from the ISU website⁶⁷ and has a comprehensive user guide. Currently, IMAPP is being used to implement the WHO/FAO Guidelines on Food Fortification with Micronutrients.¹⁶ In Uganda, it was used to identify several appropriate food vehicles and estimate the potential benefits of food fortification.⁷⁰ It was also used to simulate the impact of water with added calcium in Argentina, Bangladesh, Uganda, the Lao People's Democratic Republic, and Zambia.⁷¹

Simulation studies for the potential fortification of foods with calcium

In Canada, calcium fortification of some foods has been under evaluation. Different models were developed using data from a large national survey ($n = 1543$) to determine which scenario would most effectively reduce the proportion of the population with low intakes of calcium (mean calcium intake was 730 mg/day in women and 959 mg/day in men) while minimizing the proportion of individuals who exceeded the tolerable upper intake level.⁷² Table 2 shows different scenarios for the fortification of flour products (breads, cereals, and rice) and beverages with calcium. If flour products are fortified at 55 mg per serving, the proportion of men exceeding the upper limit for calcium (based on the usual intake of these foods) would be 2.3%. If 165 mg of calcium per serving is added to flour products, 6.3% in men would exceed the upper limit. If only non-carbonated beverages are fortified with 300 mg of calcium per serving, 3.5% of men would exceed the

upper limit, but if all types of beverages were fortified with this amount, then more than 7% of men would exceed the upper limit. For women, these scenarios have minimal impact. Therefore, a targeted fortification for women may be more appropriate in this setting.

In Finland, calcium intake is adequate so there is a concern of potential excess of calcium intake with the free circulation of calcium-fortified products as part of the European Union. Therefore, a study simulated the contribution of calcium intake from fortified foods using population-based data.⁷³ On average, calcium intake was 1197 mg/day in men and 996 mg/day in women, in which 74% came from dairy products. Different scenarios were calculated depending on the food fortified (Table 3), showing that calcium intake would exceed the upper limit in most scenarios in men. In women, this would only occur if all of these foods were replaced by their fortified version at once. However, among individuals in the lowest decile of calcium intake, only fortification of juice and wheat would be beneficial as these individuals have very low dairy product intake.

In the United States, about 50% of the population was found to consume fortified foods.⁷⁴ The prevalence of calcium intakes exceeding the upper limit was found among 1- to 3-year old's in the highest quintile (0.3%). Among adults, an increased probability of consuming calcium intake above the upper limit was also found.

The three countries described above are countries with generally high levels of calcium intake and low rates of inadequacy. Fortifying foods with calcium would not be recommended in such countries.

Table 3. Simulation study on calcium intake in Finland when ordinary foods are substituted with fortified products⁷³

Product	Level of calcium addition (mg/100 g)	Calcium intake increase (mg/day)		Total calcium intake among those with the lowest calcium decile ^a		Total calcium intake among those with the highest calcium decile ^a	
		Men	Women	Men	Women	Men	Women
Fruit juice and fruit drinks	120	158	175	~600	~550	2473	1987
Low fat and fat-free milk	180	372	214	Little change because of low intake	Little change because of low intake	2687	2026
Hot and cold breakfast cereals	80 (hot)/450 (cold)	101	91	Little change because of low intake	Little change because of low intake	2416	1903
Wheat and mixed gran bread	472	335	307	800	650	2650	2119
Total		966	787	–	–	3281	2599

^aData are ordered from lowest to highest on a scale of 1 to 10.

Excessive calcium intake (>2500 mg/per day) is not very common from the consumption of foods rich in calcium. However, this could result from the use of calcium supplements among populations with already high calcium intake from foods and this may increase the risk of hypercalcemia, renal insufficiency, milk-alkali syndrome, and even kidney stones.⁷⁵ Some studies have also shown a greater risk of cardiovascular events^{76–80} and prostate cancer,^{81,82} although more recent large meta-analyses have questioned this evidence.^{83,84} These potential risks are inconsistent, inconclusive as to causality, and insufficient to inform nutritional requirements.^{85,86} In addition, the trials using 1.5–2 g in pre-pregnant and pregnant women did not show adverse events.^{5,6} Considering that adding calcium to foods would not increase calcium intake to the levels of calcium supplementation, it seems safe to do this, particularly among populations with low calcium intake.

A potential risk of the addition of calcium to a fortification program is if it is combined with other nutritional programs in an uncoordinated way. For example, in some countries, there is fortification (mandatory or voluntary) of staple foods with one or more micronutrients, supplementation programs with some vitamins and minerals, and use of fortified blended foods or micronutrient powders for vulnerable groups. Additionally, the food industry is also voluntarily fortify-

ing a few processed foods and in some countries of Latin America, Africa, and Asia, biofortification of staple crops is also in place (more details about this have been published elsewhere).¹ Therefore, there is a concern that in some countries, particularly in high-income countries, all these events are occurring simultaneously without proper monitoring, which could lead to excessive calcium intake. This has been evident in recent reviews,^{87,88} and based on these reviews, country-specific recommendations and guidelines were developed to support the implementation, monitoring, and evaluation of the impact of food fortification programs. In particular, a National Food Fortification Board was suggested to be created in countries considering food fortification programs.^{87,88}

Factors to consider when selecting the food vehicle for calcium fortification

Selecting the food vehicle to fortify with calcium should take into account the following:

- Identify all potential foods that can be fortified with calcium in a particular setting. These should be consumed in fairly constant amounts by most individuals in the population with low or no risk of overconsumption, so that fortification levels can be accurately calculated. At the same time, it should be a food that

is affordable to the low-income groups, which are more vulnerable to low calcium intake.

- Identify foods that are processed centrally in large enough units to allow the control of the fortification process.
- Evaluate compatibility between the existing food production and distribution systems. The goal is to achieve a minimal loss of the calcium during processing, storage, and final preparation of the food.
- Assess sensory properties of the food vehicle; the addition of calcium should not lead to changes in taste, appearance, or color of the final product.
- Assess storage stability; although calcium is very stable, sedimentation could be a problem.

In certain settings, it may be better to add calcium to foods that are targeted specifically to certain populations. This will depend on the results from the baseline calcium intake data to identify the most vulnerable groups concerning calcium intake.⁸⁹ For example, if the most vulnerable group for calcium intake in a particular population are young children, then complementary foods, foods developed for school feeding programs, and special biscuits for children could be fortified with calcium. If pregnant women are the target, then special biscuits or fortified blended foods could be fortified. Also, household fortification could be designed through soluble or crushable tablets, micronutrient-based powders, spreads, and porridges.⁸⁹ This approach may be particularly helpful if other groups in the population may be at risk of excessive intake if food is fortified with calcium at the national level.

Monitoring and evaluation of calcium-fortified foods

As with any food fortification, adding calcium to foods requires adequate monitoring and evaluation, and resources should be allocated during the planning and design phase of the strategy.¹⁶ Appropriate and high-quality data-collection systems and continuous and comprehensive monitoring and evaluation systems are needed once the food fortification is initiated.⁹⁰

Regulations and national strategy

The Food and Agriculture Organization (FAO)⁹¹ established that the minimum level of any vita-

min or mineral in a fortified food per daily portion of consumption should be 15% of the WHO/FAO nutrient recommendations.⁹² The FAO also states that manufacturers should take into account the established scientific upper safe levels of these nutrients, considering different consumer groups and contributions from other sources. In the case of calcium, the upper limit (highest level likely to pose no risk of adverse health effects) is 2500–3000 mg per day.^{75,93}

Fortifying foods with calcium must follow regulations and should be designed within the country's national strategy for the prevention and control of micronutrient deficiencies.¹⁶ Several countries have established specific regulations for calcium food fortification.⁹⁴ Some specify the amount and type of calcium that can be added depending on the food vehicle and other technical details. These regulations are either done proactively, to help promote general health, or reactively, to protect the health and safety of the population.⁶⁰ However, some countries do not have well-established regulations for food fortification with calcium. If well-established regulations are not in place, the food industry could arbitrarily start fortifying foods if they can do so or start doing it because of the demand from the population for such foods. Even if the country has regulations for calcium fortification, this needs to be coordinated with other programs being implemented in that setting.

WHO/FAO guidelines for monitoring and evaluation

The monitoring and evaluation of calcium-fortified foods could follow the WHO/FAO framework.¹⁶ It should include the monitoring of the manufacturing of the calcium-fortified food to check for the quality of the food vehicle and that the amount of calcium added in the premix is adequate. Also, it should monitor the distribution in retail stores to make sure it is reaching the most vulnerable groups. Monitoring should also be done at the household level to ensure that the target population has access to the calcium-fortified food, that it is purchased and consumed in the amount predefined to have an impact, and that the calcium-fortified food is of the expected quality. Finally, it should evaluate if the calcium-fortified food is improving calcium intake at the population level and evaluate potential excessive consumption. Because there is

no available biomarker of calcium intake, dietary assessment methods are needed.

Role of government in monitoring and evaluation

Calcium food fortification requires clear legislation set by the government.⁶² Typical government actors include the Ministry of Health or Industry with specific units in charge of the management of the program, of food safety and quality, and of the nutrition information system or surveillance.⁶² Based on the WHO/FAO framework,¹⁶ GAIN developed a National Impact Model for Fortification Programs using a three-stage model⁶² that can be used for this. Also, GAIN developed the FACT toolkit with standardized methods for the collection, analysis, and synthesis of data on quality, coverage, and consumption of fortified foods across countries.^{89,95} These tools are available at www.gainhealth.org.

Monitoring intake

Calcium intake should be closely monitored using direct dietary assessment methods, such as 24-h food recall and food frequency questionnaires.⁶⁶ The same method used for the baseline should be used to evaluate the impact of the intervention. In this process, it is recommended that a logic model be used to map the different program components with its respective logical framework and matrix indicators.⁹⁶

Partnerships

Partnerships are key to this process.⁶² The public sector (government) needs to formulate the regulations of calcium-fortified foods. The private sector (industry, suppliers of the premix, food laboratories, etc.) should provide experience and expertise in food production and marketing. The social sector (academia and national consumer organizations) should advocate the importance of food fortification with calcium at the population level. However, each group has different perceptions and goals. For the public sector, the food fortification with calcium could be perceived as a cost-effective solution to low calcium intake, while for the private sector, it could be perceived as additional costs and having technical issues, but also as an opportunity to position their product with a new value. Partnerships will allow the harmonization of these issues.

Ethical and equity aspects of fortifying foods with calcium

Food fortification with calcium is subject to ethical challenges, as with any other food fortification program. The addition of calcium to foods must be informed by the right to health, based on scientific evidence, taking into account human-rights instruments for the intervention and implementation. It should benefit populations, avoid unintended harm, and promote the principles of equity and social justice.⁹⁷

In the literature, the main ethical aspects stated about food fortification are the accountability of states and/or other stakeholders and the benefits of this type of program.⁹⁸ Some of these aspects concerning calcium fortification are addressed below.

Mandatory versus voluntary fortification

Ethical considerations should also be applied when determining if calcium food fortification should be mandatory or voluntary. In this regard, the WHO recommends to determine which option would: provide the greatest benefit in the population; reduce calcium deficiency the most; be more feasible within available resources, policy frameworks, and supply and demand; and what is the configuration of the industry within the country.⁹⁷

In countries with previous mandatory fortification experience or with a food industry with previous experience with food fortification, mandatory fortification of calcium may be more feasible and even preferred. The reason is that it would provide clear guidelines on the foods and the level of calcium to fortify with, which will be standardized, eliminating the potential competition or disadvantages for those participating or not participating. As argued by Lawrence and Mark,⁶⁰ this may conflict with individual rights and interfere with personal freedoms. Furthermore, if calcium benefits the population with no potential harm to any group, it may be unethical not to implement such intervention.

In countries without a formal food industry, it could be challenging to comply with a mandatory fortification. In this case, it may be more feasible to have voluntary fortification of calcium; however, it may not reach the most vulnerable populations and may have a commercial objective, accompanied by health claims that may potentially coerce the population into believing that they need the calcium-fortified food for their well-being.⁶⁰ The food

industry may also fortify foods with calcium that are not very healthy to improve the image of their product and to claim that it is a rich source of calcium.

Benefit versus harm

When adding calcium to foods, the safety of groups not affected by low calcium intake needs to be assessed. Baseline data of calcium intake among the different groups are necessary, as discussed previously. This should be disaggregated by gender, age, rural versus urban, race and ethnicity, socioeconomic status, culture and language, occupation, religion, and other relevant social determinants (e.g., disability status, migration status, and political environment). The WHO developed guidelines on health equity⁹⁷ and an assessment toolkit⁹⁹ to help in these important issues.

Reach and access

In settings in which the calcium-fortified food is produced locally and in rural settings, a large-scale fortification approach may not reach certain households. Therefore, concurrent measures may be needed in such settings to prevent and/or mitigate health inequities due to differential access.¹⁶ Culturally appropriate messages should inform about the rationale and purpose of the calcium-fortified food, the health benefits, and even natural sources of calcium as alternative means for improving calcium intake.

Individualism versus collectivism

Policymakers should decide between individualism (autonomy and freedom to choose) versus collectivism (needs of the population as a whole).⁶⁰ These principles may help reach a decision: necessity and effectiveness of the public health intervention; the extent of the benefits versus the harms; least infringement of the intervention; and public justification of the intervention.

Final considerations

Calcium intake needs are not fulfilled in many populations. Fortifying foods with calcium could have a crucial role to improve this situation. This review has discussed the main considerations for the planning and design of fortifying foods with calcium. The type of calcium salt, food/beverage matrix, amount of calcium to be added, presence of other nutrients added, presence of enhancers or inhibitors, sensory properties, and costs are all

important considerations when adding calcium to foods. The acceptability and affordability of the food vehicle, as well as a structured and well-controlled monitoring and evaluating system to measure the reach and impact of the food fortification, are also key issues.

Since fortifying foods with calcium should be based on the actual needs and realities of a population group, country, or region, the one-size-fits-all model is not possible, as this will depend on all the factors discussed previously. A one-to-one approach for each setting may be needed.

It is important to take into consideration that fortifying foods with calcium should not replace an adequate and diverse diet. Ideally, low calcium intake could be prevented by ensuring the consumption of healthy, balanced diets with the inclusion of calcium-rich foods, such as dairy products, which are concentrated sources of calcium with high bioavailability.¹⁴ However, dairy products are not widely available, accessible, or consumed in certain regions.¹⁰⁰ Therefore, such a strategy should be part of other global strategies for improving the quality of the diet in general. This requires a level of coordination at the national level, with a multisectoral approach.

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Author contributions

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Competing interests

The authors declare no competing interests.

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