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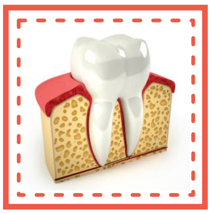
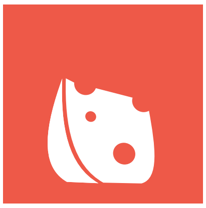
This review explores different dietary sources of calcium and how food matrix effects influence absorption of this essential mineral.

A publication for health professionals

Calcium: The essential mineral

Requirements, sources and bioavailability





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Daily calcium requirements vary across the life course, from approximately 700 mg in children to 1200–1300 mg in adolescents, older adults and pregnant or lactating women. Meeting these needs depends not only on calcium content but also on its bioavailability, which is strongly influenced by the food matrix. Dairy products remain the benchmark because they combine high calcium density with absorption enhancers such as casein, lactose and citrate while lacking strong inhibitors. The 'dairy matrix' supports sustained solubility and efficient absorption, making dairy products the most effective natural source of dietary calcium.

Many plant foods also contain calcium, but their bioavailability is often limited by phytates and oxalates, which form insoluble complexes. However, processing methods such as soaking, sprouting, fermentation and fortification can reduce the levels of these inhibitors and improve nutrient uptake. Predictive absorption models show that certain plant foods, including kale, fortified almond beverages, tofu (when low in phytates), millet and legumes such as chickpeas and kidney beans, can provide absorbable calcium equivalent to milk in up to two servings. In contrast, cereals, dried fruits and high-oxalate vegetables, such as spinach, contribute less efficiently.

Calcium is indispensable for bone integrity and critical physiological processes and lowering the risk of chronic diseases. Incorporating food matrix effects and inhibitor loads into dietary assessments offers a more realistic understanding of calcium nutrition and should guide strategies to optimise intake across life stages.

What is calcium and what does it do?

Calcium is the most abundant mineral in the human body and is an essential dietary micronutrient. An adult body contains approximately 1000 g of calcium, with approximately 99% stored in the bones, where it contributes to skeletal rigidity and serves as a mineral reservoir for maintaining blood calcium levels. The remaining 1% is distributed in extracellular fluid, intracellular compartments and cell membranes. In these sites, calcium is regulated by vitamin D, parathyroid hormone and calcitonin, and plays vital roles in muscle contraction, blood clotting, nerve transmission and blood pressure regulation.[1-3] Apart from its physiological functions and the role in maintaining bone health, dietary calcium has also been shown to have a role in the prevention of type 2 diabetes,[4] metabolic syndrome,[5] hypertension[6] and weight management.[4-7]

The body's calcium requirements vary across the life course, reflecting differences in skeletal growth, remodelling and maintenance. Calcium is essential for bone accretion during periods of rapid growth and for preserving bone mass once growth ceases. In later adulthood, when bone resorption exceeds bone formation, a net loss of calcium occurs.[3]

Obligatory calcium losses through urine, faeces and skin typically range between 150 and 300 mg/day. These inevitable losses, combined with the additional demands of growth, can only be balanced by an adequate dietary calcium intake. When dietary intake is insufficient, calcium is mobilised from bone reserves under the calcium-regulating hormones.[1,2,8] As a result, serum calcium levels are tightly maintained within a narrow range of 2.25–2.60 mmol/L by means of homeostatic control, at the expense of skeletal stores.[9]

Table 1: Dietary reference intakes for calcium by life stage (mg/day)[3]

Life stage group	Adequate intake	Estimated average requirement	Recomened dietary allowance	Tolerable upper intake level
Infants 0–6 months 7–12 months	 200 260			 1000 1500
Children 1–3 years 4–8 years		 500 800	 700 1000	 2500 2500
Adults 9–18 years 19–70 years Elderly		 1100 800 1000	 1300 1000 1200	 3000 2500/2000* 2000
Pregnant/ lactating women 14–18 years 19–30 years 31–50 years		 1100 1100 800	 1300 1000 1000	 3000 2500 2500

*Men, 51–70 years

Dietary guidelines and calcium requirements

Food-based dietary guidelines or nutrient reference intakes are used worldwide to ensure sufficient nutrient intake for general good health. In South Africa, the food-based approach is used and the guideline to 'have milk, maas or yoghurt every day' has been included specifically to address the low calcium and potassium intakes of South Africans and the high prevalence of hypertension and non-communicable diseases.[10]

The latest dietary reference intakes (DRIs) are based on current scientific evidence regarding the role of calcium in skeletal health outcomes. The estimated average requirements (EARs) and recommended dietary allowances (RDAs) established for calcium rely primarily on calcium balance studies for individuals between 1 and 50 years of age. The DRIs for calcium are listed in Table 1.[3] A notable similarity exists between the global and country-specific recommendations for daily calcium intake (800–1300 mg). One serving of dairy is calculated to provide 300 mg of calcium; therefore, three servings of dairy per day should allow most age groups to meet their daily calcium requirements.

Calcium cannot be synthesised by the body and must be obtained from food. A food is considered a good source of calcium when it has a high calcium content of high bioavailability, a combination that has long been recognised in dairy products.[11] Dairy products are the richest dietary sources of calcium, while other foods such as sardines, tofu (with calcium), beans (red, white), certain fruit (e.g. figs) and vegetables (e.g. spinach, sweet potato and broccoli), almonds and salmon also contain calcium.[1] Recent research emphasises calcium bioaccessibility, a prerequisite for its intestinal absorption and eventual bioavailability, and the effect of the food matrix, specifically the dairy matrix, on calcium accessibility, absorption and bioavaliability.[11-15]

The dairy matrix

Dairy products are rich in various nutrients, including proteins, fats, vitamins, minerals, lactose and sometimes probiotics. The interaction of these elements and the structures they form create what is known as the dairy matrix. This matrix varies among products such as milk, yoghurt and cheese, and is influenced by the type of milk and processing techniques used. It can be examined at different levels: molecular (protein structures), microscopic (protein networks), and macroscopic (textures). These structural differences affect nutrient digestion and absorption, as well as physiological responses, such as feelings of fullness. Notably, liquid and semi-solid dairy products can have different effects even if they contain the same amount of calories.[14]

Calcium bioaccessibility refers to the fraction of calcium released from the food matrix during digestion and which is thus available for uptake in the intestine.[13] In dairy products, calcium is stored in casein micelles and complexes with citrate and sometimes lactose, which maintain it in a soluble, dispersed form, making it more accessible during digestion. Conversely, many plant foods contain phytates, oxalates or fibres that bind calcium into insoluble complexes, such as calcium oxalate in spinach, thereby limiting its release and accessibility.[12,13,15] Muleya et al.[11] evaluated the bioaccessibility of calcium from plant-based products relative to that from bovine milk (Table 2).

Only a few foods matched milk with regard to bioaccessible calcium, with kale, finger millet porridge, black chickpeas and kidney beans being the leading sources.

Calcium absorption

Calcium is absorbed primarily in the duodenum by an active transcellular and saturable system, which is stimulated and regulated by vitamin D, and through passive and vitamin D-independent paracellular transport in the jejunum, ileum and even in the colon (approximately 4%) when the intake is high.[8] The food matrix modulates how efficiently released calcium crosses the intestinal epithelium, with only ionised calcium (Ca^{2+}) being absorbed. Components such as lactose, proteins, citrate and vitamin D in dairy products keep calcium soluble and stimulate transport mechanisms, thereby enhancing absorption. However, milk is not naturally a rich source of vitamin D unless fortified, an uncommon practice in South Africa.

The buffering capacity of milk proteins, phosphates and citrates also slows gastric acidification, allowing for a gradual release of colloidal calcium phosphate and promoting steady, efficient absorption, rather than a rapid but less effective spike, as seen with isolated salts. In contrast, phytates in cereals and legumes and oxalates in foods such as spinach or rhubarb bind calcium in insoluble complexes, significantly reducing its availability for absorption despite adequate release during digestion or bioaccessibility.[12,13,15]

Weaver et al.[16] developed an algorithm to predict fractional calcium absorption from foods on the basis of calcium load and oxalate and phytate loads, which represent the two main inhibitors of calcium absorption. The fractional calcium absorption of the foods listed in Table 2, as well as their corresponding serving equivalents to milk, was calculated using these two equations. Using the predicted fractional absorption makes most foods'

Table 2: Gross and bioaccessible calcium compositions of plant-based products and their predicted fractional absorption compared with skimmed milk[11,16]

Food product	Ca (mg/100 g fw)	Bioaccessibility (%)	Bioaccessible Ca (mg) per serving	Servings equivalent to milk	Oxalate (g)	Phytate (g)	Predicted fractional absorption (%)[f]	Servings equivalent to milk
Skimmed milk (200 ml)	**121 ± 3.73**	**29.9 ± 9.52**	**72.4 ± 23.0**	**1**	**0**	**0**	**36**	**1**
Cereals								
Millet porridge[a,b] (160 g)	161 ± 0.60	21.8 ± 5.46	56.3 ± 14.1	1.3	0.03–0.09	0.37–0.68	33–34	1
Oat porridge[b] (160 g)	16.2 ± 0.34	9.32 ± 1.02	2.42 ± 0.26	30	0.002–0.01	0.27–0.47	57	5.9
Basmati rice[c] (150 g)	13.8 ± 0.43	34.5 ± 4.32	7.16 ± 0.90	10	0.001–0.005	0.01– 0.04	60	7.1
Legumes (150 g)								
Tofu	322 ± 19.8	4.09 ± 0.59	13.2 ± 1.91	5.5	0.013–0.019	0.05–3.705	22–29	0.7
Lentils	46.9 ± 1.52	22.6 ± 1.894	15.9 ± 1.33	4.6	0.253–0.434	0.408–0.707	42–44	2.9
Peas	34.7 ± 2.49	46.5 ± 2.42	24.2 ± 1.26	3.0	0.245–0.441	0–0.3	45–48	3.6
Chickpeas	68.4 ± 1.75	26.9 ± 5.35	27.7 ± 5.49	2.6	0.138 – 0.321	0.3–0.84	39–42	2.1
Black chickpeas	108 ± 3.16	24.2 ± 3.18	39.2 ± 5.14	1.8	0.138 – 0.321	0.3–0.84	35–38	1.5
Kidney beans[d]	140 ± 2.88	18.7 ± 0.49	39.3 ± 1.02	1.8	0.015–0.09	0.3–0.6	35–37	1.2
Vegetables (80 g)								
Spinach	201 ± 21.3	0.13 ± 0.02	0.206 ± 0.04	352	0.6–1	0–0.05	28–33	1.8
Broccoli	52.8 ± 0.7	59.9 ± 3.70	25.3 ± 1.56	2.9	0.001–0.005	0–0.02	28–33	3.9
Cabbage	68.4 ± 1.92	47.3 ± 1.97	25.9 ± 1.08	2.8	0.001–0.005	0–0.02	53	3.2
Kale	959 ± 121	42.7 ± 2.37	328 ± 18.2	0.2	0.001–0.005	0–0.02	50	0.5
Plant-based beverages (200 ml)								
Soya drink	46.9 ± 1.87	3.45 ± 0.22	3.24 ± 0.20	22.3	0.005–0.02	0.1–0.4	44–45	2.1
Oat drink[e]	154 ± 47.6	3.22 ± 0.39	9.89 ± 1.19	7.3	0.002–0.01	0.1–0.4	33	0.9
Rice drink[e]	120 ± 7.29	5.16 ± 0.29	12.4 ± 0.71	5.8	0.002–0.01	0.01–0.05	36	1
Almond drink[e]	379 ± 7.42	3.59 ± 0.35	27.2 ± 2.65	2.7	0.02–0.12	0.2–1	22–24	0.5
Dried fruits & other								
Tahini (5 g)	118 ± 2.6	4.90 ± 0.23	0.29 ± 0.01	250	0.002–0.01	0.04–0.06	72	20.1
Prunes (30 g)	42.0 ± 3.91	43.2 ± 1.58	5.45 ± 0.20	13.3	0.008–0.015	0.01–0.02	64	10.8
Figs (30 g)	180 ± 8.43	10.7 ± 0.99	5.74 ± 0.54	12.6	0.006–0.012	0.01–0.03	50	3.2
Apricots (30 g)	82.5 ± 14.3	34.7 ± 1.64	8.59 ± 0.41	8.4	0–0.002	0.01–0.03	58	6.1
Raisins (30 g)	61.7 ± 6.33	47.4 ± 1.55	8.78 ± 0.29	8.2	0.002–0.005	0.01–0.03	61	7.8

Values are means ± standard deviation of three replicates. Means from each food group were compared with skimmed milk. (a) Finger millet; (b) Whole grains; (c) Refined grains; (d) Includes calcium chloride added as a firming agent; (e) Fortified with either di- or tri-calcium phosphate; (f) Fractional absorption = 0.889−0.0964ln(Ca load in mg)−0.115(oxalate g)−0.019(phytate g) calcium bioavailability more comparable to that of milk than estimates based on in vitro bioaccessibility, with the largest discrepancies found for spinach, tofu and almond drinks. Bioaccessibility alone may under- or overestimate nutritional value, and including phytate/oxalate effects provides a more realistic picture. Kale, fortified almond drinks, tofu (if low in phytate), millet and legumes such as chickpeas and beans are the best plant sources of calcium based on their calculated fractional absorption (≤2 servings equal to milk).

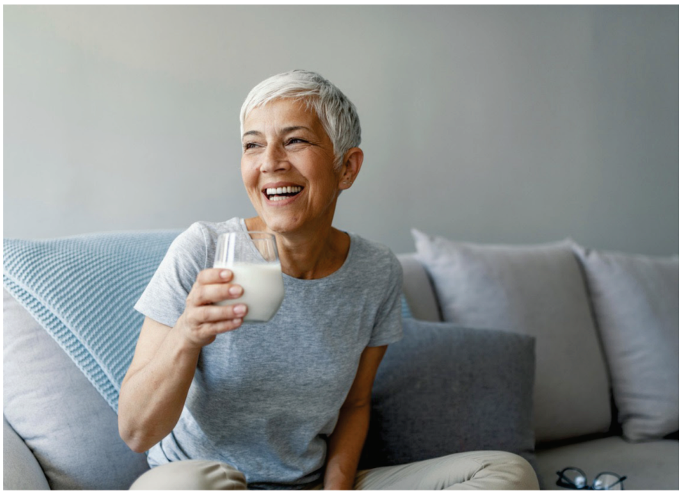
The bioavailability of calcium from food

Calcium bioavailability refers to the proportion of ingested calcium that is ultimately absorbed and used for physiological functions, which is strongly influenced by the food matrix. Dairy foods are considered the gold standard because they combine high calcium density with absorption enhancers, such as proteins, lactose and citrate, while also lacking inhibitors such as phytates and oxalates. Their buffering capacity allows for a slow, sustained release of calcium, which promotes efficient uptake and contributes to high bioavailability. Many plant foods, although sometimes rich in calcium, show lower bioavailability owing to binding compounds that form insoluble complexes. Food processing methods, such as soaking, fermentation and fortification, can alter the food matrix by reducing inhibitors or adding enhancers, thereby improving calcium bioavailability.[12,13,15]

Conclusion

Calcium plays a vital role in human health, with its importance extending beyond bone health to other physiological functions. The dairy matrix significantly influences calcium bioaccessibility, absorption and bioavailability, making dairy products particularly effective sources of this essential mineral. Although some plant-based foods can provide calcium, their bioavailability often falls short of that of dairy products because of the presence of inhibitory compounds.

Understanding the complex interplay between food matrices and calcium absorption is crucial for developing effective dietary strategies to meet calcium requirements across different life stages. As research continues to uncover the intricacies of calcium metabolism and its interactions within various food matrices, it is becoming increasingly clear that both the quantity and quality of dietary calcium sources are important considerations for optimal health outcomes.



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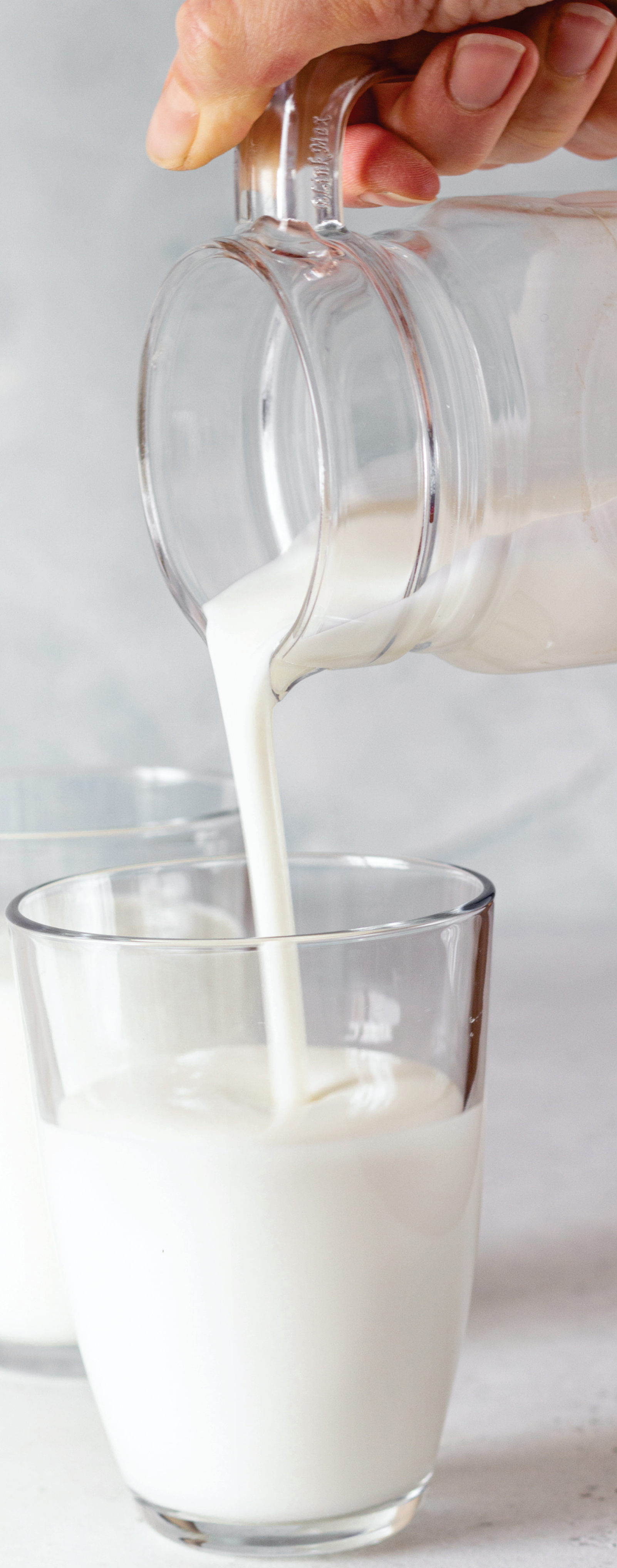

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