



The Effect of Thermal Processing Temperature on the Bioavailability of Micronutrients in Vegetables

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Abstract

Thermal processing alters the content and accessibility of micronutrients in vegetable matrices in a non-linear and class-dependent manner. The authors systematise data from 35 peer-reviewed publications dated 2002 to 2025, including the two foundational INFOGEST protocols, and map four temperature windows (60 to 80, 80 to 100, 100 to 120 and above 120 °C) onto six classes of micronutrients: vitamin C, B-vitamins together with folate, carotenoids, polyphenols, minerals, and glucosinolates with their isothiocyanate hydrolysis products. The authors operationally distinguish retention, the fraction of a micronutrient remaining in the product after processing, from bioaccessibility, the fraction released into the gastrointestinal lumen under the INFOGEST static in-vitro model, and demonstrate that heating may simultaneously decrease retention and increase bioaccessibility, accounting for the heating paradox observed in tomato. The 80 to 100 °C window maximises bioaccessibility of carotenoids and fat-soluble vitamins through cell-wall disruption; the 60 to 80 °C window lowers phytate to mineral molar ratios without proportional gain in absorption; the 100 to 120 °C window drives lycopene cis to trans isomerisation with a peak in bioaccessibility; above 120 °C thermo-oxidative carotenoid degradation coexists with acrylamide formation in asparagine-rich matrices. No universal temperature optimum simultaneously satisfies all six classes; a working compromise lies within 80 to 100 °C, while for thermolabile vitamin C and folate the optimum shifts to sous-vide at 60 to 80 °C. The contribution is a taxonomy of temperature windows, a cross-class matrix and an operational separation of retention and bioaccessibility within a single quantitative framework.

Keywords: Acrylamide, Bioaccessibility, Carotenoids, Folate, INFOGEST, Lycopene Isomerisation, Micronutrient Bioavailability, Phytate, Retention, Sous-Vide, Temperature Windows, Thermal Processing of Vegetables.

ABBREVIATIONS

AsA — ascorbic acid; AUC — area under the curve; BCMO1 — beta-carotene 15,15'-monooxygenase 1; DHA — dehydroascorbic acid; EFSA — European Food Safety Authority; INFOGEST — international consortium static in-vitro digestion protocol; ISX — intestine-specific homeobox transcription factor; PPO — polyphenol oxidase; SR-BI — scavenger receptor class B type 1; TAC — total antioxidant capacity; WHO — World Health Organization.

INTRODUCTION

Vegetables remain the principal dietary source of vitamin C, folate, carotenoids, several polyphenols and minerals in most diets, and they are consumed predominantly after thermal processing rather than raw [1, 2]. A practical contradiction follows immediately. Heat destroys thermolabile compounds while simultaneously increasing the accessibility of lipophilic nutrients through cell-wall breakdown and modification of the food matrix [3, 4]. Coe and Spiro summarise losses

incurred during domestic cooking for a wide set of vegetables and show that the simple choice between boiling and steaming changes the final vitamin C content by tens of percentage points even when the target temperature is held constant [1]. Jia and colleagues, in a 2025 review, document that storage and processing can both decrease and increase the bioaccessibility of phytochemicals in fruit and vegetable products, with the direction of the effect depending on temperature, exposure time and the matrix itself [2].

Global trends in vegetable consumption sharpen the practical relevance of the question. WHO recommends a daily intake of at least 400 g of fruits and vegetables, yet population-level intake in most regions remains below this benchmark, and the share of vegetables consumed as part of processed or ready-to-eat meals continues to grow. In high-income countries the share of vegetables consumed cooked or otherwise heat-processed exceeds eighty percent for several staple categories, including potatoes, tomatoes and cruciferous vegetables. Industrial processing introduces a second layer of

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thermal exposure on top of domestic cooking, since blanching, pasteurisation, retort sterilisation and frying define the temperature history of the product before it ever reaches the home kitchen. As a result, the same nominal vegetable category may arrive at the consumer with a wide range of effective thermal histories, and dietary recommendations framed around raw equivalents systematically misrepresent the realised micronutrient delivery.

Domestic and industrial cooking practices contribute differently to the realised temperature history of a vegetable. Domestic cooking concentrates heat events at boiling temperatures around 100 °C and at frying temperatures around 180 °C, with limited use of intermediate or sub-boiling regimes outside specialist cuisine. Industrial processing, by contrast, applies blanching at 80 to 95 °C as a routine pre-step for freezing, drying or canning, followed by retort sterilisation at temperatures above 121 °C for shelf-stable canned products. As a result, even the same vegetable cultivar harvested from the same field can reach the consumer through several distinct thermal histories, with implications for the realised retention and bioaccessibility that have not been mapped onto a single quantitative framework. The four-window taxonomy proposed in the present review is intended to provide such a framework by anchoring the discussion in dominant biochemical mechanisms rather than in cooking-method labels.

Regulatory framing reinforces the need for a temperature-aware view of vegetable processing. EFSA monitors acrylamide as a process-induced contaminant, with benchmark levels set for fried potato products and other heat-processed foods rich in asparagine and reducing sugars. The European Commission has issued specific mitigation rules for fried vegetable products under Regulation (EU) 2017/2158, while WHO and national agencies maintain advisory guidance on phytate-rich plant foods in the context of iron and zinc deficiency. These positions imply that any framework describing vegetable processing must address both nutrient delivery and the formation of unwanted secondary products, and must do so on a continuum of temperature rather than by a binary cooked or raw classification. The notion of personalised nutrition, with growing interest in tailoring micronutrient delivery to genotype and life stage, further increases the demand for a unified description that links processing parameters to absorbable dose.

The literature on thermal processing of vegetables is fragmented along the lines of nutrient class. Saini and colleagues cover carotenoids and their bioavailability in fruits and vegetables [3]. Gibson, Raboy and King concentrate on phytate and minerals [5]. Fratianni and colleagues document lipophilic bioactive compounds after boiling and steaming [4]. A unifying temperature map covering all six micronutrient classes simultaneously has not been identified by the authors after a structured search of Scopus, Web of

Science and CrossRef across the years 2015 to 2025. This gap defines the task of the present review.

The terminological distinction between retention, bioaccessibility and bioavailability shapes the interpretation of the data. Retention denotes the fraction of a micronutrient remaining in the product after processing and is measured by mass balance before and after heating [6, 7]. Bioaccessibility denotes the fraction of a micronutrient released from the matrix into the gastrointestinal lumen and available for intestinal uptake, measured by the standardised INFOGEST in-vitro static digestion model [8, 9]. Bioavailability denotes the fraction of an ingested compound that reaches the systemic circulation and is determined by the in-vivo plasma response or area-under-the-curve metric [10]. The three metrics must be separated explicitly, since the same heat treatment may decrease retention, increase bioaccessibility and leave bioavailability unchanged because of inter-individual variability in absorption [10, 11]. Throughout the present review the umbrella term bioavailability is used in section titles and general framing only, while every quantitative claim is qualified by the specific metric it refers to.

The objective of the work is to systematise data from 35 peer-reviewed publications on the influence of thermal processing temperature on retention and bioaccessibility of six micronutrient classes across the range from 60 to 180 °C. The specific tasks are threefold. The first is to construct a taxonomy of four temperature windows defined by the dominant biochemical mechanism in each window. The second is to assemble a cross-class matrix linking six nutrient classes to four temperature windows by their expected effect on retention and bioaccessibility. The third is to compare the principal cooking methods at matched target temperatures, including sous-vide, steaming, microwaving, boiling, baking with concentrated tomato as the working example, and deep-frying. The article is positioned as a narrative review without claims to new experimental data. The contribution lies in synthesis and taxonomy, including the formal separation of the three metrics, the consolidation of disparate nutrient classes into a single temperature grid and the description of five governing mechanisms by which temperature acts on the food matrix: thermal degradation, cis to trans isomerisation, cell-wall disruption, hydrolysis of antinutrients, and formation of secondary products through the Maillard reaction.

METHODS

The work is performed in the format of a narrative review. It differs from a systematic literature review and from a PRISMA-compliant analysis by the absence of a formal meta-analytic sample and quantitative effect synthesis. Coverage is instead controlled by a thematic grid of eight search directions agreed before the inclusion phase, with explicit numerical targets for the number of sources per direction. The

narrative format was chosen because the existing literature on temperature effects in vegetables is heterogeneous in design, in matrix and in measurement protocol, with very few head-to-head comparisons of cooking methods on a single matrix using a common analytical pipeline. Under these conditions a quantitative meta-analysis would require effect-size synthesis across non-comparable units, while a structured narrative synthesis preserves the qualitative direction of effects together with quantitative anchors where they are available.

The search was performed in Scopus, Web of Science and CrossRef for the period 2015 to 2025. Two foundational older sources were retained outside this window: Minekus 2014 [8] and Dewanto 2002 [12]. A third foundational source, Brodkorb 2019 [9], falls within the window by year but is treated as foundational on a par with [8] because it defines the extended INFOGEST 2.0 protocol used by the majority of recent bioaccessibility studies. The two INFOGEST protocols differ in the specification of bile salt concentration, in the activity definitions for pepsin and pancreatin, and in the recommended electrolyte composition for the simulated salivary, gastric and intestinal fluids; the 2019 update also adds explicit checkpoints for the brush-border phase and for sample collection, which materially affect comparability of bioaccessibility values across laboratories.

Search queries were constructed along eight directions, namely thermal degradation kinetics of vitamin C; retention of B-vitamins and folate; bioaccessibility of carotenoids and matrix effects; stability and bioaccessibility of polyphenols; mineral bioavailability and phytate hydrolysis; comparative cooking methods; the INFOGEST in-vitro digestion standard; and the Maillard reaction, acrylamide formation and antinutrients at high temperature. The keywords used in combination across directions were thermal processing, blanching, boiling, steaming, microwave, sous-vide, roasting, deep-frying, vegetable, retention, bioaccessibility, bioavailability, INFOGEST, phytate, lycopene, glucosinolate, sulforaphane and acrylamide. Boolean composition followed the pattern (cooking term) AND (vegetable term) AND (metric term), with a typical query of the form (boiling OR steaming OR microwave OR sous-vide) AND (vegetable OR potato OR broccoli OR tomato OR carrot OR spinach) AND (retention OR bioaccessibility OR bioavailability OR INFOGEST).

Each direction received a target number of sources at the planning stage, ranging from two to seven, and the actual harvest was checked against the target during the inclusion phase. When a direction yielded more candidates than the target, preference was given to studies that reported both retention and bioaccessibility on the same matrix, that specified the processing temperature within a narrow band rather than a wide window, and that used a recognised digestion protocol (preferably INFOGEST) rather than an in-house variation. When a direction yielded fewer candidates

than the target, the date window was extended back to 2014 to capture foundational protocol publications, and the geographic scope was opened beyond European and North American journals to include Asian and South American food-science publications indexed in Scopus.

Inclusion criteria covered a vegetable matrix, an explicit specification of the processing temperature, measured indicators of retention or bioaccessibility (or a validated biochemical analysis allowing back-calculation), and publication in a peer-reviewed journal indexed in Scopus or Web of Science. Exclusion criteria covered non-vegetable matrices such as cereals, fish and mushrooms (with potatoes retained as a tuberous vegetable), publications without a specified temperature, journals without confirmed indexing, and duplicate sources covering a less complete sample of vegetables than another already retained. Every DOI was verified through api.crossref.org/works/{DOI} with a check of the first author, the title, the journal, the year and the volume; mismatch on any one field led to rejection. The final sample comprised 35 sources distributed by direction as follows: vitamin C (4 sources), B-vitamins and folate (3), carotenoids and matrix effects (7), polyphenols (3), minerals and phytate (4), comparative cooking methods (7), INFOGEST (3), Maillard reaction and acrylamide (2), and cross-functional reviews (2).

The standard for assessing bioaccessibility is the INFOGEST static in-vitro digestion protocol. The 2014 version was developed by international consensus and prescribes fixed enzyme activities, pH targets and incubation times for three sequential phases of digestion: oral, gastric and intestinal with duodenal secretions [8]. The 2019 extension in Nature Protocols refines enzyme activities, the composition of electrolyte solutions and checkpoint definitions, and adds optional brush-border digestion as a fourth phase [9]. Both versions model a static system without peristalsis and without consideration of colonic microbiota, so the in-vitro indicator is used in the present review as a proxy for comparison between processing treatments rather than an absolute predictor of human absorption [8, 9, 10]. Degradation kinetics for thermolabile vitamins in vegetables are described to a first approximation by a first-order rate equation with an Arrhenius-type temperature dependence of the rate constant [6, 13]. For carrots, potatoes and amaranth in the range 70 to 100 °C, Eyarkai Nambi and colleagues report apparent activation energies for ascorbate degradation of approximately 30 to 50 kJ/mol [6]. Van Boekel and Roux, in a multilevel analysis, confirm the applicability of such a model to heterogeneous matrices and at the same time emphasise the need to incorporate batch and cultivar variability into the parameter estimation [13].

Limitations of the narrative-review method itself must be stated explicitly. The first limitation is selection bias. A narrative grid built before the search may overrepresent

direction-specific evidence and underrepresent cross-cutting work that does not fit the eight-direction taxonomy. The authors mitigated this risk by retaining two cross-functional reviews that span more than one direction and by allowing each direction to admit cooking-method comparisons as supplementary evidence. The second limitation is the absence of a quantitative effect-size synthesis. The matrix in the Results section is qualitative on the cell level (high, medium, low retention; increased, comparable, decreased bioaccessibility) with quantitative anchors stated for individual studies, rather than a pooled estimate per cell. The third limitation is publication bias in favour of positive effects, which is structural in the cooking-comparison literature. The fourth limitation is the dominance of in-vitro INFOGEST as the bioaccessibility metric, which is discussed

in the Discussion section. Across the 35 sources only a few report indirect human-absorption data, and randomised controlled trials directly comparing cooking methods on the same matrix for the same micronutrient have not been identified. The majority of bioaccessibility data is therefore obtained under INFOGEST, which sets the upper bound for the generalisability of the conclusions. The fraction of dehydroascorbic acid in total vitamin C, the choice of carotenoid extraction solvent, and the choice of INFOGEST phase for measuring bioaccessibility differ between laboratories [14, 7, 15]. Regional and cultivar heterogeneity of matrices adds further variance; Lisciani and colleagues report differences in mineral retention of up to a factor of 1.5 between varieties of the same vegetable cooked by the same method [16].

RESULTS

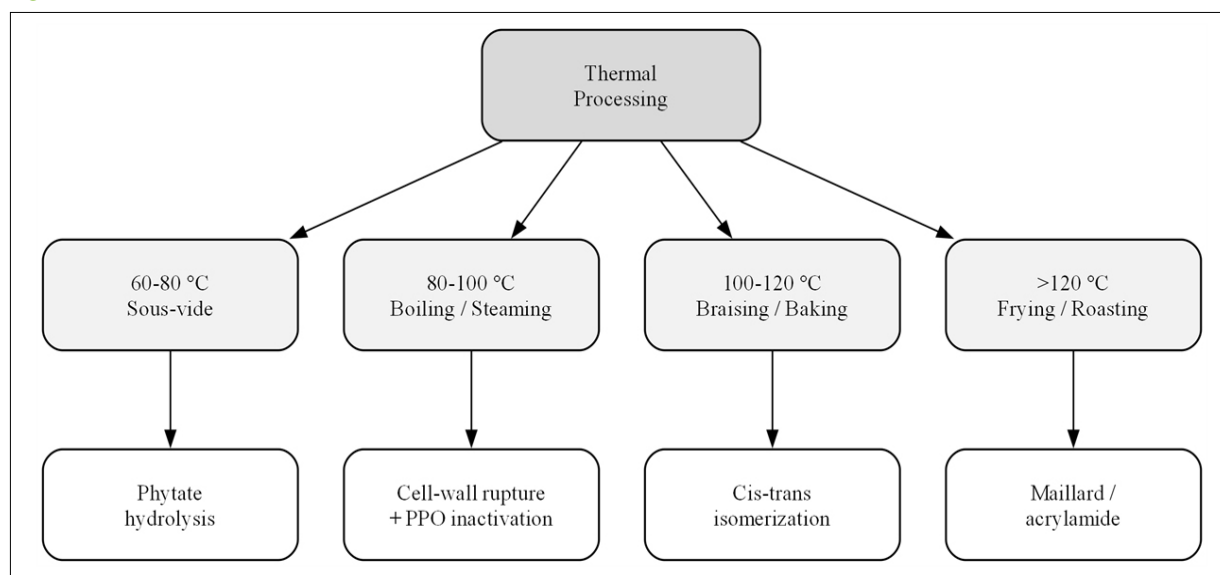


Figure 1. Taxonomy of four temperature windows of thermal processing of vegetables and the dominant biochemical mechanisms governing micronutrient bioavailability.

The results are organised in three layers. The first layer is a taxonomy of four temperature windows defined by the dominant biochemical mechanism in each window. The second layer is a sequential review of six micronutrient classes within and across these windows. The third layer is a comparison of five principal cooking methods at matched target temperatures.

The first temperature window (60 to 80 °C) corresponds to sous-vide and to low-temperature regimes in domestic and industrial practice. The dominant mechanism is the hydrolysis of phytate together with a partial matrix effect, with minimal degradation of vitamins. Gibson and colleagues establish molar thresholds of phytate to iron above 1 and phytate to zinc above 15 as predictors of low mineral absorption and show that soaking and heating in this range lower the molar ratios [5]. Zhang and colleagues critically revisit phytate to metal interactions and confirm that endogenous phytase becomes inactivated above 70 °C, while in the band 50 to 70 °C the enzyme retains activity and can reduce phytate

content during sufficiently long incubation [17]. Florkiewicz and Berski apply sous-vide as an alternative to traditional boiling for a wide set of vegetables and report maximum retention of potassium, calcium and magnesium at 70 °C for 60 minutes; the difference relative to boiling reaches 10 to 25 percent of the micronutrient mass [18]. The window also accommodates partial inactivation of polyphenol oxidase in some matrices, although full inactivation typically requires the second window. From the standpoint of carotenoid bioaccessibility the first window is unfavourable: the temperature is insufficient to disrupt the chromoplast envelope and to release lycopene and lutein into the lipid phase of digestion, so bioaccessibility values remain close to those measured for the raw matrix.

The second window (80 to 100 °C) covers boiling, steaming and most standard blanching protocols. The dominant mechanisms are the disruption of the cell wall and of matrix barriers, the inactivation of polyphenol oxidase, the early stages of cis to trans isomerisation of carotenoids, and the

loss of thermolabile vitamins by first-order kinetics [6, 13, 12, 19]. Eyarkai Nambi and colleagues report for blanching of carrot at 90 °C a vitamin C loss of up to 30 percent within the first 5 minutes, with concurrent retention of more than 70 percent of phenolic compounds [6]. Iqbal and colleagues describe the inactivation of polyphenol oxidase at 80 to 95 °C as the key step for stabilising the polyphenol pool of vegetables and preventing oxidative browning during downstream processing [19]. Iborra-Bernad and colleagues, in a comparison of physico-chemical and structural parameters after sous-vide, cook-vide and conventional boiling, show that boiling at 95 °C softens the cell wall more aggressively, increasing the diffusion of soluble compounds into the cooking water [20]. Fratianni and colleagues document that, after correction for soluble-solid losses during boiling and steaming, the true content of lutein and beta-carotene in leafy greens decreases by 15 to 20 percent, while the apparent increase in fresh-weight basis is an artefact of the leaching of water-soluble mass from the matrix [4]. A further important observation in this window is that the temperature plateau corresponds to the boiling point of water at atmospheric pressure, so that domestic cooking saturates near 100 °C regardless of the heat source, and the duration of exposure becomes the principal control variable.

The third window (100 to 120 °C) includes short baking at limited moisture, simmering in a closed vessel under modest pressure, and the final stages of thermal processing of concentrated tomato products. The dominant mechanism is cis to trans isomerisation of carotenoids, with a peak in lycopene bioaccessibility, accompanied by accelerated losses of folate and thermolabile polyphenols [21, 22, 23, 24, 15]. Honda and colleagues describe the kinetics of lycopene isomerisation in tomato pulp and report that the cis-isomer fraction increases from a single-digit percent in fresh pulp up to approximately 30 to 35 percent after roughly 30 minutes at 110 °C, which improves extractability and in-vitro bioaccessibility [21]. Czarnowska-Kujawska and colleagues, comparing folate retention under different cooking methods in broccoli and spinach, show that boiling at 100 °C for 10 minutes lowers folate in broccoli by 45 to 55 percent, while sous-vide at 90 °C for 30 minutes lowers it only by 15 to 20 percent [22]. Phan and colleagues document that joint INFOGEST incubation of red cabbage with cherry tomato increases the bioaccessibility of anthocyanins from cabbage but decreases the bioaccessibility of carotenoids from tomato by 20 to 30 percent through competition for mixed micelles [23]. The third window is therefore both the productive zone for tomato-based products and the zone where folate-rich green vegetables already incur substantial losses, which forces a trade-off when the dish combines both classes.

The fourth window (above 120 °C) covers deep-frying, pan-frying and roasting with surface drying. The dominant mechanisms are the Maillard reaction, the formation of

acrylamide through the participation of asparagine and reducing sugars, and the thermo-oxidative degradation of carotenoids and ascorbate [25, 26, 12]. Yang and colleagues investigate acrylamide formation in French fries and report a sharp rise in concentration from 150 to 800 µg/kg as the frying temperature increases from 160 to 190 °C at a fixed duration of 4 minutes [25]. Chan models a two-step frying profile (first stage at 140 °C, second stage at 175 °C) and shows a reduction in final acrylamide concentration of 30 to 45 percent while preserving sensory parameters [26]. Dewanto and colleagues, in their classical 2002 work, report for tomato heated at 88 °C an increase in extractable lycopene and total antioxidant activity together with a decrease in vitamin C retention, illustrating the dissociation of the two metrics at moderate temperatures and the transition to net loss with further heating beyond the second window [12]. The fourth window combines two risk dimensions: the accelerated loss of nutritional quality, and the appearance of process-induced contaminants subject to regulatory monitoring.

Vitamin C in vegetables follows first-order kinetics with respect to ascorbic acid and concurrent oxidation to dehydroascorbic acid; both forms are biologically active, so a summed indicator is methodologically preferable to separate quantification of the two species [14, 6]. Eyarkai Nambi and colleagues calculate apparent activation energies of 30 to 45 kJ/mol for blanching and report a retention fraction of 70 percent for carrot at 90 °C and 5 minutes [6]. Van Boekel and Roux, in a multilevel analysis, emphasise that batch-to-batch variability reaches 15 to 20 percent and must be incorporated into the kinetic model rather than absorbed into a single mean [13]. Vieira and colleagues, comparing boiling, steaming and microwaving of galega kale, report that the AsA to DHA ratio shifts towards the oxidised form during boiling (approximately 4 to 6) and stays close to the original distribution during steaming (approximately 8 to 2) [14]. Mugo and colleagues quantify losses of potassium and vitamins during blanching of leafy greens and document that blanching of spinach at 90 °C for 3 minutes reduces vitamin C by 35 to 45 percent, while potassium is lost only by 12 to 18 percent because of the slower diffusion of inorganic ions through the cell wall [27]. Lee and colleagues calculate the true retention of B1, B2, B3 and vitamin C in spinach, carrot and zucchini and show that microwaving with minimal water gives the highest retention for all four nutrients simultaneously, with values consistently above the boiling baseline [7]. Across eight cultivars of potato, Liu and colleagues report that steaming preserves 60 to 75 percent of vitamin C and comparable shares of folate (B9) and vitamin E, with substantial cultivar-to-cultivar variability that has direct implications for breeding programmes targeting micronutrient quality [28]. The combined picture across these studies suggests an operational threshold near 90 °C, below which losses of vitamin C are constrained to

about a quarter of the initial content for short cooking times and above which they accelerate sharply, consistent with the activation energies reported for blanching kinetics [6]. Practical recommendations therefore have to specify both the temperature and the duration in tandem rather than either parameter alone.

An additional consideration for vitamin C concerns the reuse of cooking water. When boiling is selected as the cooking method and the cooking water is discarded, the loss accounts for both the chemical degradation of ascorbic acid and the leaching of intact vitamin C into the aqueous phase, with the leaching component often dominating the reported retention figure for short cooking times. When the cooking water is preserved, for example as the base of a soup or sauce, the leached fraction returns to the dish and the effective retention of the meal as a whole is materially higher than the retention measured for the solid component alone. This distinction does not appear consistently in the cooking-comparison literature, since most studies report retention for the solid portion only, but it directly affects practical recommendations for households and for catering. A consistent application of mass-balance reasoning across the solid and aqueous fractions of a cooked dish would close part of the gap between laboratory measurements and the realised dietary delivery [1, 27].

B-vitamins and folate exhibit divergent thermolability. Thiamine (B1) degrades already at 80 °C; riboflavin (B2) is more stable; folate is particularly sensitive to oxidation and to heating in the aqueous phase, with reported losses driven both by chemical degradation and by leaching of the water-soluble vitamin [29, 7, 22]. Maharaj and colleagues evaluate folate content and retention in vegetables typical of the South Pacific region and report loss coefficients of 30 to 60 percent during boiling and 15 to 30 percent during steaming, with notable matrix dependence between leafy and fruit-type vegetables [29]. Czarnowska-Kujawska and colleagues directly compare four cooking methods for folate in broccoli and spinach: sous-vide at 90 °C for 30 minutes yields retention of 80 to 85 percent, boiling at 100 °C for 10 minutes yields 45 to 55 percent, steaming at 100 °C for 7 minutes yields 65 to 75 percent, and microwaving gives intermediate values [22]. Lee and colleagues report for spinach a true retention of thiamine of 70 to 80 percent under steaming compared with 50 to 60 percent under boiling, again confirming the protective role of restricted water contact for water-soluble B-vitamins [7]. For potato, Liu and colleagues show a cultivar-level spread in retention of folate (B9) and vitamin E of 15 to 25 percentage points under the same steaming regime, which limits the operational utility of an averaged value and motivates cultivar-specific cooking guidance for vitamin-targeted dishes [28].

Carotenoids show the most pronounced manifestation of the heating paradox. In a 2015 review, Saini, Nile and Park

systematise the chemistry, analytics and bioavailability of carotenoids and document that thermal treatment simultaneously decreases retention and increases bioaccessibility through the release of compounds from chromoplasts and lipoprotein complexes within the cell [3]. Dewanto and colleagues were the first to quantify this effect in tomato at 88 °C [12]. Honda and colleagues describe the kinetics of cis to trans isomerisation of lycopene at 90 to 120 °C and show that 5-cis, 9-cis and 13-cis isomers exhibit higher solubility in mixed micelles and, as a consequence, higher bioaccessibility than the all-trans form [21]. Carpentieri and colleagues confirm the link between the cis-isomer fraction and lycopene bioaccessibility under INFOGEST after various thermal pretreatments of tomato processing by-products [15]. Dai and colleagues, comparing whole tomato juice produced by microfluidisation with thermally processed juice, show that disruption of the cell wall increases lycopene bioaccessibility by a factor of 2 to 4 regardless of the disruption mechanism, confirming that wall integrity rather than thermal degradation is the dominant constraint on lycopene release in the intact fruit [24]. Sriwichai and colleagues directly show for spinach that partial disintegration of the cell wall during boiling increases the bioaccessibility of vitamin K1 (phylloquinone) and allow extrapolation of the mechanism to other lipophilic micronutrients including beta-carotene and lutein [30]. In joint cooking of red cabbage with cherry tomato, Phan and colleagues document a 20 to 30 percent decrease in carotenoid bioaccessibility in the presence of anthocyanins through competition in the lipid phase of digestion, indicating that mixed-class dishes cannot be evaluated by single-class arguments alone [23]. Comparing steaming and boiling of carrot, spinach, zucchini and broccoli, Fratianni and colleagues demonstrate that, at matched target temperatures, steaming and boiling produce comparable true retention of lutein and beta-carotene after correction for mass loss, and that the apparent increase in carotenoids in boiled product is an artefact of soluble-solid leaching rather than a real concentration effect [4]. Borel and Desmarchelier, in an Annual Review, emphasise that in-vitro bioaccessibility values translate into in-vivo bioavailability with a correction for polymorphisms in SR-BI, BCMO1 and other transporters and enzymes, contributing 30 to 50 percent inter-individual variability on top of the averaged values [10]. Numerical anchors across the carotenoid literature converge on a small set of practical reference points. Lycopene bioaccessibility from raw tomato pulp is typically below 1 percent, rises to single-digit percent values after cell-wall disruption alone, and reaches values in the band of 10 to 25 percent after combined disruption and cis-isomerisation in the third window [3, 21, 24]. Beta-carotene bioaccessibility from raw carrot rises by a factor of 2 to 3 after steaming or boiling [3, 4]. Lutein bioaccessibility from spinach increases roughly in parallel with vitamin K1 bioaccessibility under partial cell-wall disintegration [30]. These anchors define the realised gain expected from

cooking and serve as a quantitative reference against which any new processing technology can be benchmarked.

Polyphenols in vegetables include flavonoids, anthocyanins and phenolic acids in free and cell-wall-bound forms. Jakobek and Matic review non-covalent interactions between dietary fibre and polyphenols and show that thermal processing disrupts hydrogen bonds and hydrophobic contacts, partially releasing bound polyphenols into the soluble fraction [31]. Iqbal and colleagues document the inactivation of polyphenol oxidase at 80 to 95 °C as a precondition for preserving the free polyphenol fraction and preventing enzymatic oxidative browning, which would otherwise consume part of the available pool [19]. Jia and colleagues, in their 2025 review, document that polyphenol bioaccessibility varies non-linearly with temperature: moderate heating increases the released fraction through matrix breakdown, while further heating reduces it through thermal degradation and formation of complexes with proteins [2]. In the joint cooking experiment with red cabbage and cherry tomato, Phan and colleagues report an increase in anthocyanin bioaccessibility of 25 to 40 percent in the mixed matrix relative to isolated cooking of cabbage, illustrating positive matrix interactions under simultaneous processing of complementary vegetables [23]. The polyphenol class therefore illustrates a central feature of the temperature taxonomy, namely a non-monotonic dependence of bioaccessibility on temperature with a maximum near the transition between the second and third windows. A further consideration is the matrix-specific distribution of polyphenols between the soluble and the cell-wall-bound fractions. In leafy greens the bound fraction can exceed half of the total polyphenol pool, while in fruit-type vegetables the soluble fraction dominates. The released amount under heating therefore depends not only on the temperature window but also on the initial partition between the two fractions, so that a recommendation tuned to one matrix may not transfer to another even within the same temperature window.

An additional window-specific note for polyphenols concerns the interaction with the cooking water. In boiling, a fraction of free polyphenols leaches from the matrix into the cooking water, and the loss can reach 30 to 40 percent for water-soluble flavonoids in shorter cooking times. Steam, by contrast, retains the soluble polyphenol fraction within the matrix at the cost of a smaller release of bound polyphenols. Microwaving with minimal water occupies an intermediate position, with retention values that frequently exceed those of boiling by 10 to 25 percentage points for the soluble fraction while approaching those of steaming for the bound fraction [19, 31, 2]. The resulting ranking of methods for polyphenols therefore aligns with that for vitamin C in the second window but diverges in the third window because of the formation of polyphenol to protein complexes at higher temperatures.

Minerals (iron, zinc, calcium, magnesium, potassium) are

lost predominantly through diffusion into the cooking water, while their bioavailability is constrained by the formation of phytate complexes. Gibson, Raboy and King, in a review in *Nutrition Reviews*, document that values of phytate to iron above 1 and phytate to zinc above 15 are associated with low absorption of iron and zinc in human populations and that soaking together with mild heating reduces these molar ratios through activation of endogenous phytase and enzymatic hydrolysis [5]. Zhang and colleagues critically revisit phytate to metal interactions and emphasise that a reduction in phytate content does not translate into a proportional rise in absorption because polyphenols, oxalate and calcium also compete for the same metal cations [17]. Huertas and colleagues experimentally compare boiling, soaking and various culinary treatments of the common bean and show that iron bioaccessibility ranges from 5 to 24 percent depending on the cultivar and method, even when retention of the mineral itself remains broadly comparable [32]. Across typical Italian vegetables (zucchini, eggplant, potato), Lisciani and colleagues compare grilling, microwaving and steaming and document heterogeneous mineral-retention profiles: steaming best preserves potassium, phosphorus, iron and zinc in potato, while microwaving best preserves minerals in zucchini, and grilling best preserves them in eggplant, with differences reaching a factor of 1.5 between varieties of the same vegetable type [16]. Corte-Real and Bohn, in a review of interactions between divalent metals and fat-soluble compounds in the gastrointestinal tract, show that calcium and magnesium ions can decrease carotenoid bioaccessibility by 20 to 35 percent through precipitation of bile salts and disruption of mixed-micelle formation, providing a direct mechanistic link between the mineral and carotenoid classes within the same digestion event [11].

Glucosinolates of cruciferous vegetables and their hydrolysis products, in particular sulforaphane, respond to temperature in a non-linear manner because of the involvement of endogenous myrosinase and the epithiospecifier protein. Soares and colleagues, in a 2017 review, describe the effect of boiling, steaming, microwaving and roasting on the glucosinolate content and on vitamin C in broccoli and document that boiling at 100 °C for 5 minutes leaches 25 to 55 percent of glucosinolates into the cooking water, while steaming preserves 80 to 95 percent at the cost of myrosinase inactivation above 70 °C [33]. Lu and colleagues experimentally confirm that microwave processing of broccoli with temperature control in the band 50 to 60 °C raises the sulforaphane yield by approximately 80 percent relative to conventional heating, with an additional gain of approximately 40 percent achieved by increasing microwave power from 475 to 950 W; the mechanism is attributed to differential thermal stability of myrosinase and the epithiospecifier protein [33, 34]. Applying INFOGEST modelling to raw and processed cruciferous vegetables, Martínez-Castro and colleagues report that bioaccessibility

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of sulforaphane and of inorganic micronutrients varies between 30 and 75 percent depending on the species and the processing method [35]. The class is therefore a matrix-

specific case that does not fully fit the general temperature taxonomy and that requires a separate kinetic interpretation tied to the activity profile of the responsible enzymes.

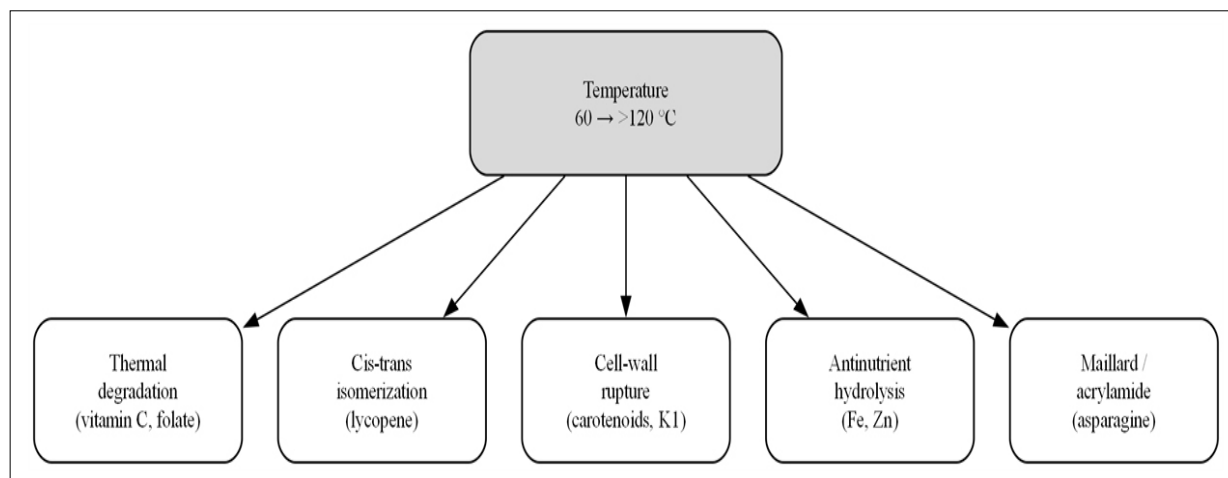


Figure 2. Five principal mechanisms by which thermal processing temperature acts on micronutrient bioavailability in the vegetable matrix: thermal degradation, cis to trans isomerisation, cell-wall disruption, hydrolysis of antinutrients, and formation of secondary products through the Maillard reaction.

The cross-class matrix consolidates the foregoing class-by-class results into a single representation (Table 1), with one cell per pair of nutrient class and temperature window.

Table 1. Cross-class matrix «micronutrient class times temperature window leading to expected effect on retention and bioaccessibility».

Class	Window I (60–80 °C)	Window II (80–100 °C)	Window III (100–120 °C)	Window IV (above 120 °C)
Vitamin C	retention high (above 85 percent), bioaccessibility close to raw [7, 14, 27]	retention 55–75 percent, bioaccessibility comparable [6-7, 28]	retention 30–55 percent, accelerated losses [6, 13]	retention below 30 percent, thermo-oxidative degradation [12, 25]
B-vitamins and folate	folate retention 80–85 percent, sous-vide optimum [22]	folate retention 45–75 percent [7, 22, 29]	folate retention 30–50 percent [22, 28]	retention below 30 percent, breakdown of pteridine ring [29]
Carotenoids	retention high, bioaccessibility limited by intact matrix [3, 30]	true retention comparable to raw after mass-loss correction; bioaccessibility raised through cell-wall disruption [3-4, 30]	peak lycopene bioaccessibility through cis-isomerisation [21, 24, 15]	thermo-oxidative degradation, net loss [12]
Polyphenols	retention high, polyphenol oxidase inactivation incomplete [19, 31]	bioaccessibility increased by 25–40 percent through matrix release [2, 19, 23]	retention decreased, formation of protein complexes [2, 23]	degradation and Maillard complexation [12, 25]
Minerals	phytate hydrolysis, retention above 85 percent [5, 17, 18]	retention of K and Mg decreased by 15–30 percent depending on method and matrix [27, 16]	retention decreased through leaching [32, 16]	retention high, but bioaccessibility decreased through complexation [11, 16]
Glucosinolates and isothiocyanates	retention above 90 percent, myrosinase active; microwave processing with temperature control at 50–60 °C raises sulforaphane yield by approximately 80 percent [33-35]	steaming preserves 80–95 percent, boiling leaches 25–55 percent [33-34]	degradation beyond thermal stability [33]	breakdown, loss of activity [33]

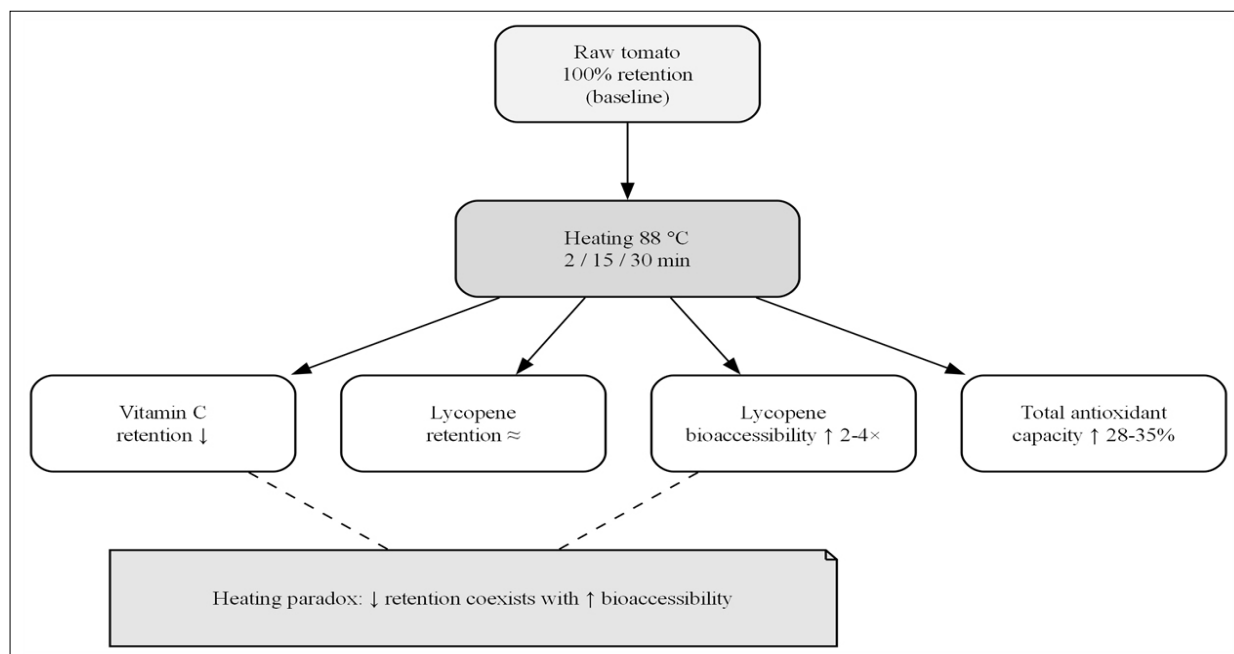


Figure 3. The heating paradox in tomato: simultaneous decrease in vitamin C retention and increase in lycopene bioaccessibility under boiling at 88 °C, reproduced from Dewanto and colleagues (2002) [12].

A comparison of the principal cooking methods at matched target temperatures is given in Table 2. Iborra-Bernad and colleagues document that sous-vide minimises the diffusion of soluble compounds into the aqueous phase through hermetic packaging, which preserves not only minerals but also water-soluble vitamins [20]. Florkiewicz and Berski show that sous-vide maximises mineral retention across a wide set of vegetables compared with boiling and steaming, with the largest gains observed for potassium and magnesium [18]. Fratianni and colleagues document that steaming provides a balance between the preservation of thermolabile vitamins and the elevation of bioaccessibility for carotenoids [4]. Coe and Spiro, in their review of domestic cooking, confirm that microwaving with minimal water exceeds boiling for the retention of vitamin C and folate by 15 to 30 percentage points, with the gain attributable to the combination of short heating time and limited contact with water [1]. For potato, Liu and colleagues show that steaming at 100 °C for 30 minutes preserves 60 to 85 percent of vitamin C and thiamine depending on cultivar, again pointing to the cultivar dimension of cooking optimisation [28]. The split of cooking methods into the six rows of Table 2 follows operational practice in domestic and industrial kitchens, where each method targets a distinct combination of temperature, water contact and exposure duration.

Table 2. Comparison of six cooking methods of vegetables by integral effect on retention and bioaccessibility (qualitative indicator: up arrow indicates higher than raw, approximately equal indicates comparable, down arrow indicates lower than raw).

Method	Target temperature	Vitamin C, retention	Folate, retention	Carotenoids, bioaccessibility	Minerals, retention	Sources
Sous-vide	60–80 °C, 30–60 min	↑↑	↑↑	=	↑↑	[20, 18, 22]
Steaming	95–100 °C, 5–15 min	↑	↑	↑↑	↑	[4, 7, 16, 28]
Microwaving	80–100 °C, 2–6 min	↑↑	↑	↑	↑	[14, 7, 34, 1]
Boiling	95–100 °C, 5–15 min	↓	↓↓	↓	↓↓	[6, 22, 16, 33]
Baking (concentrated tomato, near 110 °C)	100–120 °C, 10–60 min	↓	↓	↑↑ for lycopene	=	[21, 15, 12]
Deep-frying (potato, 175–190 °C)	160–200 °C, 5–30 min	↓↓	↓↓	↓	=	[25, 26, 12]

DISCUSSION

The data consolidated in the cross-class matrix support the central thesis of the review. The heating paradox, first quantified by Dewanto and colleagues for tomato at 88 °C [12], is reproduced in the works of Carpentieri, Dai and Honda for lycopene [15, 24, 21] and in the work of

Sriwichai and Fratianni for fat-soluble vitamins [30, 4]. In these cases retention drops by 10 to 30 percent while bioaccessibility rises by a factor of 2 to 4, which shifts the interpretation of thermal processing from unambiguously destructive to differentiated by metric. The implication is that recommendations on cooking should specify the metric of interest, since maximising retention and maximising

bioaccessibility are different optimisation problems with different optimal temperatures.

In the 2022 review by Coe and Spiro, the practical conclusion is that steaming and microwaving are the preferred domestic methods [1]; Fratianni and colleagues complement this with bioaccessibility data showing the advantage of steaming for carotenoids [4]. The present review places these results into a single temperature grid with explicit identification of the dominant mechanism in each window, whereas in Coe and Spiro the cooking method is the primary axis and temperature a derived parameter [1]. The advantage of the proposed taxonomy is the ability to predict the qualitative effect for a new nutrient class or a new matrix from the corresponding window without reproducing the entire experimental basis. The label «compromise» applied to the 80 to 100 °C window is qualitative: the window combines a positive effect on carotenoids and fat-soluble vitamins through cell-wall disruption with an acceptable effect on thermolabile vitamins relative to the third and fourth windows, without claiming a quantitative optimum in any aggregated metric, since such an aggregated metric does not exist within the current literature.

The mechanism of *cis* to *trans* isomerisation of carotenoids deserves separate attention because of its direct quantitative consequences. Honda and colleagues show that the *cis*-isomer fraction of lycopene in tomato pulp grows from a single-digit initial level up to approximately 30 to 35 percent after about 30 minutes at 110 °C [21]. Carpentieri and colleagues link this shift to an increase in bioaccessibility measured under INFOGEST [15]. The correlation is explained by the higher solubility of *cis*-forms in mixed micelles in the duodenal phase; postabsorptive incorporation into chylomicrons falls outside the INFOGEST framework and requires *in-vivo* confirmation [10]. Borel and Desmarchelier emphasise that *in-vivo* bioavailability in humans is further modulated by polymorphisms in SR-BI, BCMO1 and ISX, and that averaged *in-vitro* values translate into population-level estimates only with a correction of 30 to 50 percent [10]. This limits the value of INFOGEST data for individual recommendations and preserves their value for comparative evaluation of processing treatments at the population level.

The mechanism of cell-wall disruption is dominant in the second window. Sriwichai and colleagues directly measure the bioaccessibility of vitamin K1 in spinach before and after boiling and report a factor of 1.8 to 2.5 increase together with retention of 75 to 85 percent [30]. Saini and colleagues, in their carotenoid review, summarise data on chromoplast opening in carrot and spinach at typical boiling and steaming temperatures (about 85 to 95 °C) and connect the process with the release of membrane-associated carotenoids into the lipid phase [3]. Phan and colleagues add the inverse side: competition for mixed micelles between anthocyanins from red cabbage and carotenoids from tomato during joint cooking [23]. The implication is that an increase in the

bioaccessibility of one class within a mixed matrix may be accompanied by a decrease in the bioaccessibility of another class, so that any aggregated indicator described as «the bioavailability of a dish» requires balancing across classes rather than maximising any one of them.

First-order kinetics for the thermolabile vitamins C and folate set an upper bound on the safe temperature for vitamin-targeted dishes. Eyarkai Nambi and colleagues show that activation energies of 30 to 45 kJ/mol correspond to a factor of 2 to 3 acceleration of degradation per 10 °C increase in temperature [6]. Czarnowska-Kujawska and colleagues experimentally confirm that a transition from 90 °C for 30 minutes (*sous-vide*) to 100 °C for 10 minutes (boiling) at a comparable temperature integral produces a twofold loss of folate [22]. Mugo, Lee and Liu add quantitative estimates for spinach, carrot and potato [27, 7, 28]. Vieira and colleagues document the shift in the AsA to DHA ratio towards the oxidised form during boiling [14]. These data justify the recommendation of *sous-vide* as a first-choice regime for dishes with a high contribution of thermolabile nutrients to the total nutrient delivery of the meal.

The phytate-hydrolysis paradox requires careful interpretation. Gibson and colleagues establish molar thresholds of phytate to iron and phytate to zinc as formal predictors of absorption [5]; Zhang and colleagues warn that a reduction in phytate does not translate into a proportional rise in absorption because of competing modulators including polyphenols, oxalate and calcium [17]. Huertas and colleagues experimentally report iron bioaccessibility in the bean of 5 to 24 percent without a direct correlation with mineral retention [32]. For typical Italian vegetables, Lisciani and colleagues show that steaming preserves minerals best in potato, while for zucchini and eggplant the optimal method is different, which highlights the matrix dependence of recommendations [16]. Corte-Real and Bohn close the logical loop: even at high retention, elevated concentrations of calcium and magnesium reduce carotenoid bioaccessibility through bile-salt precipitation and disruption of mixed-micelle formation [11]. The implication is that optimisation of one class (minerals through *sous-vide*) may change the bioaccessibility of another class (carotenoids) within the same meal portion, so that temperature recommendations cannot be derived for one class in isolation.

A practical observation that follows from the heating paradox is that the comparative ranking of cooking methods depends sharply on which class of micronutrients is taken as the optimisation target. For thermolabile water-soluble vitamins the ranking favours *sous-vide* and microwaving, with steaming close behind and boiling clearly worst. For carotenoid bioaccessibility the ranking favours steaming and intermediate-temperature baking, with boiling acceptable when the cooking water is reused and frying useful only for fat-soluble release that is rarely realised in practice because of competing oxidative losses. For minerals the

ranking again favours sous-vide and steaming over boiling, but with substantial matrix-dependent reordering between zucchini, eggplant and potato as documented by Lisciani and colleagues [16]. No single ranking is therefore valid across all classes, and the design of a balanced meal requires either a primary class to optimise or an explicit compromise rule across classes.

The case of cruciferous vegetables and sulforaphane stands apart from the general temperature taxonomy. Lu and colleagues report that microwave processing of broccoli at controlled temperature in the band 50 to 60 °C increases the sulforaphane yield by approximately 80 percent relative to conventional heating, with an additional gain on raising microwave power up to 950 W [34]. Soares and colleagues attribute the effect to the inactivation of the epithiospecifier protein at 60 to 70 °C while myrosinase remains active up to about 75 °C [33]. Martínez-Castro and colleagues document, under INFOGEST modelling, a variability of the bioaccessibility of sulforaphane and inorganic micronutrients of 30 to 75 percent [35]. These data show that, for specific enzyme-substrate pairs, temperature optimisation can fall outside the general taxonomy and requires an individual kinetic map keyed to enzyme stability rather than to bulk thermal effects.

High-temperature regimes (above 120 °C) generate a double risk that combines the loss of micronutrients with the formation of secondary toxicants. Yang and colleagues report for French fries an increase in acrylamide concentration from 150 to 800 µg/kg as the temperature rises from 160 to 190 °C [25]. Chan models a two-stage profile of 140 °C followed by 175 °C and shows a 30 to 45 percent reduction in the final acrylamide concentration while preserving sensory parameters [26]. In the original work on tomato at 88 °C, Dewanto and colleagues directly demonstrate the transition of the heating paradox into a regime of net losses as the temperature moves beyond the productive window [12]. The implication is that for dishes based on potato and other asparagine-rich vegetables the temperature profile becomes a risk variable rather than only a nutritional efficiency variable.

A further methodological observation concerns the analytical pipeline that links retention and bioaccessibility within a single experiment. The literature contains very few studies in which both metrics are measured on the same matrix, with the same processing parameters and within the same laboratory, so that the matrix cells in Table 1 inevitably combine retention values from one set of studies with bioaccessibility values from another. This is a structural source of variance that no individual study can remove. Standardisation efforts within the INFOGEST consortium have moved towards integrated reporting, but the practical adoption rate among cooking-comparison studies is uneven. A second methodological observation concerns the temperature itself as an experimental variable. The reported values often denote either the set point of the

cooking equipment or the temperature of the surrounding water, while the temperature inside the vegetable matrix may differ by several degrees and may follow a distinct time profile depending on the thermal diffusivity and the geometry of the piece. A blanching study at 90 °C therefore covers a range of internal temperatures, which contributes to the spread of retention values observed across nominally identical regimes.

A direct consequence of the cross-class matrix concerns the gap between industrial and domestic cooking. Industrial processing operates at controlled temperature and time and applies blanching, pasteurisation or sterilisation under explicit thermal targets, with a primary objective of microbiological safety and shelf life. Domestic cooking, by contrast, is dominated by atmospheric boiling near 100 °C and by frying in oil with temperature control limited to surface visual cues, so that the realised temperature history is subject to wide variability. The taxonomy proposed here can be read as a normative grid for industrial recipe design, where the choice of window is explicit, but it also points to a clear opportunity for domestic guidance focused on duration rather than peak temperature, since the latter is constrained by water boiling and by oil-frying conventions. A second consequence concerns ready-meal vegetables and frozen produce. Industrial blanching before freezing is a standard step that inactivates polyphenol oxidase and stabilises colour, and it is performed within the second window. The temperature history of a frozen vegetable therefore includes one second-window pass, plus a domestic reheating step that often pushes the same matrix into the third window. The cumulative effect on carotenoids is favourable through repeated cell-wall disruption, while the effect on folate and vitamin C is unfavourable because the integral over time of degradation kinetics is what matters, not the peak temperature alone. Reformulation of frozen-vegetable recommendations from «reheat thoroughly» towards «reheat briefly with steam» follows directly from the present taxonomy.

The limitations of the present review are layered. The first limitation is the dominance of in-vitro INFOGEST over in-vivo evidence; only Borel, Desmarchelier and Gibson and colleagues offer indirect data on human absorption [10, 5]. Randomised controlled trials directly comparing cooking methods on the same vegetable for the same micronutrient have not been identified within the sample. The second limitation is a deficit of Maillard literature on vegetables outside potato; the two sources covering the fourth window [25, 26] both describe French fries, while Maillard effects in carrot, spinach and tomato above 120 °C are not systematically described in the indexed literature. The third limitation concerns regional and cultivar heterogeneity of matrices. Lisciani and colleagues report a spread of mineral retention up to a factor of 1.5 between varieties of the same vegetable [16], and Liu and colleagues report a cultivar-level spread of thiamine retention in potato of 20 to 25

percentage points under the same steaming regime [28]. The fourth limitation concerns differences in analytical protocols for retention and bioaccessibility between laboratories, including the share of dehydroascorbic acid measured, the choice of carotenoid extraction solvent, and the choice of INFOGEST phase for measuring bioaccessibility [14, 7, 15]. The fifth limitation is the genetic variability of human absorption through SR-BI, BCMO1 and other transporters [10], which makes population means indicative rather than prescriptive at the individual level.

Implications for practice and for further research follow from the matrix and from the limitations. For domestic cooking, sous-vide at 60 to 80 °C is preferred when the aim is to preserve thermolabile vitamins, and steaming at 95 to 100 °C is preferred when the aim is to raise the bioaccessibility of carotenoids and fat-soluble compounds. Microwaving with minimal water serves as a compromise method and as the only method that materially raises the sulforaphane yield in broccoli [34]. Boiling remains acceptable for large root vegetables provided that the cooking water is reused (in soups, stocks or sauces), which recovers part of the soluble nutrients lost by diffusion [16, 1]. For the food industry, two-stage temperature profiles deliver a balance between sensory quality and acrylamide reduction [26]. For the research agenda, three priority directions follow. The first is randomised in-vivo studies comparing cooking methods on the same matrix and the same micronutrient. The second is the expansion of Maillard studies to non-potato vegetable matrices, in particular roasted carrot, baked tomato and oven-cooked spinach in fat-rich preparations. The third is the standardisation of simultaneous measurement of retention and bioaccessibility within a single experimental series, ideally with paired sampling of the solid and the aqueous fractions of the cooked dish.

A separate implication concerns culinary education and consumer-facing communication. The taxonomy of temperature windows can be expressed in plain language as a four-band scale that maps onto the controls of typical kitchen appliances, including the dial of an oven, the wattage setting of a microwave and the temperature display of a sous-vide bath. Such a four-band scale, accompanied by class-by-class guidance similar to that of Table 1 but in simplified form, would allow consumers to make explicit trade-offs at the level of the meal rather than at the level of the individual ingredient. Industrial actors can use the same scale as a normative reference for product design, which is particularly relevant for ready-meal vegetables where the choice of pre-cooking temperature determines both the realised micronutrient delivery to the consumer and the residual capacity of the product for further heating without quality loss.

CONCLUSION

A universal temperature optimum that simultaneously maximises the bioavailability of all six micronutrient classes

in vegetables has not been identified within the sample of 35 peer-reviewed publications dated 2002 to 2025. The 80 to 100 °C window functions as a compromise regime that raises the bioaccessibility of carotenoids and fat-soluble vitamins through cell-wall disruption and partially inactivates antinutrients, while preserving the majority of thermolabile vitamins. The 60 to 80 °C window (sous-vide) minimises losses of vitamin C and folate and, with sufficient moisture, lowers phytate to mineral molar ratios, although the rise in mineral absorption is not proportional because polyphenols, oxalate and calcium also compete for the metal cations [17]. The 100 to 120 °C window provides the peak in lycopene bioaccessibility through cis to trans isomerisation at the cost of accelerated folate degradation. The window above 120 °C combines thermo-oxidative degradation of carotenoids and ascorbate with acrylamide formation in asparagine-rich matrices, particularly in potato; for other vegetable matrices above 120 °C the systematic data are limited [25, 26, 12].

Four practical recommendations follow from the taxonomy. The first is to apply sous-vide for broccoli, spinach and leafy greens with high folate content [22, 29]. The second is to apply steaming at 95 to 100 °C for carrot, tomato and spinach when the goal is to raise the bioaccessibility of carotenoids [4, 30]. The third is to apply microwaving with minimal water for broccoli when the goal is to maximise the sulforaphane yield [34]. The fourth is to apply two-stage temperature profiles for potato deep-frying when the goal is to lower acrylamide [26]. All four recommendations are formulated as comparative statements between cooking methods applied to the same matrix and do not account for inter-individual variability in absorption at the level of the consumer.

Open questions for further work remain both quantitative and methodological. Randomised controlled trials comparing cooking methods on a single vegetable matrix for human bioavailability are required [1, 10]. The expansion of Maillard literature to non-potato vegetable matrices above 120 °C is required [26]. The standardisation of simultaneous measurement of retention and bioaccessibility in a single experimental series is required to remove inter-laboratory variability [4, 9]. The advance of these three directions in parallel would convert the proposed taxonomy of temperature windows from a qualitative map into a quantitative model that predicts the bioavailability of micronutrients in vegetables after thermal processing. A natural extension of such a quantitative model is its coupling with AI-driven kinetic modelling of bioaccessibility, in which a parametrised digital twin of the digestion process accepts processing temperature, exposure time and matrix descriptors as inputs and returns a class-resolved bioaccessibility profile as output. With sufficient training data, including paired retention and INFOGEST measurements on common vegetables, such a model can support recipe-level optimisation in the food industry as well as personalised recommendations conditioned on genotype and life stage. The taxonomy of temperature windows proposed here is intended to provide

the qualitative scaffold on which such quantitative tools can be built, and to function in the meantime as a transparent and reproducible framework for both academic synthesis and culinary practice.

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