SENSORY AND PHYSICOCHEMICAL CHANGES IN RAINBOW TROUT MEAT UNDER DIFFERENT PRESERVATION AND STORAGE CONDITIONS. A NARRATIVE REVIEW

C. E. Nistor, C. T. Cîrmaciu (Florea)*, G. V. Hoha, A. Usturoi, P. Macovei, B. Păsărin

Faculty of Food and Animal Sciences, Iasi University of Life Sciences, Iaşi, Romania

Abstract

This narrative review summarises how chilling and superchilling, freezing, salting and smoking affect the sensory and physicochemical quality of rainbow trout (Oncorhynchus mykiss) meat, compares the indicators used to define shelf life and identifies methodological limitations and research gaps. Literature was searched between July and September 2026 in seven databases; primary studies were synthesised qualitatively and shelf-life values were not pooled. Shelf life was strongly endpoint-dependent and varied with product form, temperature, packaging, salt level, smoking method and additives, and single indices such as TVB-N or peroxide value were unreliable on their own. Freezing slowed microbial growth but did not prevent lipid and protein oxidation, texture change and pigment fading. Salting and smoking extended storage life but involved sensory trade-offs. Multi-endpoint designs combining sensory, microbiological and physicochemical measures are recommended.

Key words: *rainbow trout, sensory quality, shelf life, freezing, smokin*

INTRODUCTION

Rainbow trout (*Oncorhynchus mykiss*) is one of the most widely farmed freshwater fish; its world production was reported at 739,500 t in 2020, equivalent to 1.5% of global inland aquaculture output, and the species is appreciated for its taste and nutritional properties [1]. Besides fresh consumption, it is frequently frozen or smoked [2], and it has a high commercial value in Europe [3]. Fish flesh is, however, highly perishable, and freshness is one of the main determinants of its quality and market value [3], [4].

Deterioration of trout reflects interacting microbial, enzymatic, oxidative and structural changes, and its rate depends on temperature, product form and handling: filleting shortened the microbiological and sensory life of iced trout from 15–16 days (whole fish) to 10–12 days [5], and gutted trout could be kept for about three weeks on ice against two weeks for ungutted fish [6]. Four groups of treatments are used to slow these changes: chilling and superchilling, that mainly lower the rate of deterioration [7]; freezing, which stops microbial growth but may not prevent lipid and protein oxidation or texture change [8], [9]; salting and curing, which alter water activity, texture and flavour [10], [11]; and smoking, a centuries-old preservation technique [3] in which salt, partial drying and smoke components act together to delay microbiological and oxidative spoilage [2] and to create the characteristic flavour [1]. These treatments are often combined with

*Corresponding author: catalina.florea@iuls.ro
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vacuum or modified-atmosphere packaging and natural antimicrobials.

Smoked products also carry specific hazards: smoke generation can form polycyclic aromatic hydrocarbons (PAHs), whose formation depends strongly on smoke temperature and fuel, and a regulatory maximum for benzo[a]pyrene applies in the European Union [1]. Studies that measure such hazards together with quality are scarce, and the sensory and chemical endpoints used to define shelf life differ widely. The Quality Index Method (QIM), first developed in Tasmania, scores skin, eyes, gills and abdomen in demerit points that increase with storage time [4]; because no QIM scheme specific to rainbow trout has been accepted by the QIM Eurofish Alliance, the farmed-salmon scheme (maximum 24 points) has been applied, and 15 demerit points (14 ± 2 days on ice) have been proposed as the rejection point of ungutted trout [4]. Other studies relied on trained panels [3], experienced panellists [2] or non-professional assessors [12], and on different chemical limits, such as TVB-N limits of 35 mg N/100 g [3] or 40 mg N/100 g [12], so that shelf-life values are difficult to compare.

The scientific literature on rainbow trout preservation has progressed from early investigations into ice storage and texture [13], through sensory and microbial characterisation of whole and filleted trout [5], to comparative analyses of chilling and superchilling, packaging strategies, curing, and smoking [7, 14]. Published studies nevertheless differ in product form, temperature, packaging and endpoint definitions, which complicates direct comparison. This paper aims to summarise how these methods affect the sensory and physicochemical quality of rainbow trout meat, compare the indicators used to define shelf life, and identify methodological limitations and research gaps.

MATERIAL AND METHOD

Literature review was conducted between July and September 2026 in PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, OpenAlex and Semantic Scholar. Search terms combined rainbow trout or *Oncorhynchus mykiss* with terms for storage and processing (chilled storage, superchilling, freezing, packaging, salting, brining, cold smoking, hot smoking, liquid smoke) and quality endpoints (sensory quality, lipid oxidation, shelf life). Were included primary studies on rainbow trout reporting sensory and/or physicochemical outcomes under a defined storage or processing condition; studies on other species or without a storage component were excluded. Studies differ in product form, temperature, packaging atmosphere, sensory scales and endpoint definitions. Results were synthesised, and shelf-life values were not pooled or ranked. Studies on a closely related salmonid (Arctic char) were consulted only for methodological context and are identified where cited.

RESULTS AND DISCUSSION

Chilled and superchilled raw trout

The clearest cross-study pattern is that refrigerated storage progressively reduces sensory quality while microbial and biochemical changes accumulate, but the pace depends on the unit being stored and on temperature. In a chilled-storage assessment of farmed trout on ice, sensory and microbiological results placed shelf life at about 9–11 days; TVB-N (total volatile basic nitrogen) fluctuated, and the authors found that it was not a dependable stand-alone quality index [15]. A separate whole-versus-fillet study found sensory/microbial shelf life of 15–16 days for whole ungutted trout and 10–12 days for fillets, bacterial counts and several chemical spoilage values were higher in fillets, consistent with greater deterioration after filleting [5]. A commercial case study reported lower quality-index scores (i.e. fresher fish) in gutted trout and a maximum ice-storage life of 3 weeks for gutted versus 2 weeks for ungutted fish [6]. Gutting and filleting are

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different interventions assessed with different endpoints, so they cannot be combined into a single effect of pre-storage processing (Figure 1). A QIM study of ungutted trout (n = 36) stored on ice at 0.6–0.8°C for 21 days used the 24-point farmed-salmon scheme and five trained panellists: the quality index increased linearly with storage time ($R^2 = 0.966$) and reached 15.3 at day 14, and the authors proposed 14 ± 2 days or 15 demerit points as the maximum shelf life of ungutted trout; gill and abdominal odours deteriorated earlier than skin odour [4]. This is consistent with the 2-week maximum reported for ungutted fish [6]. Temperature control can extend the interval before rejection. In a direct comparison of −3°C superchilling and 3°C chilling, composite acceptability based on sensory score, total aerobic count and K-value was 11 days at −3°C and 5 days at 3°C [7]. A temperature-response study across −3 to 9°C similarly found that total aerobic counts, electrical conductivity and K-value increase while sensory scores fell, with faster change at higher temperatures; an artificial neural network predicted the measured quality variables more effectively than the Arrhenius models tested [16]. These findings support temperature as a strong determinant, but the shelf-life values should not be generalized beyond their experimental protocols. An investigation of ice-temperature storage combined with chitosan, tea polyphenols and lemon juice found lower TVB-N and lower pH (the latter partly attributable to the acidic lemon juice) than 0°C or 4°C controls, consistent with a combined effect of low temperature and bio-preservatives [17]. Sensory deterioration also has a physical and structural component. Ice-stored trout became softer over 11 days, with texture differing by dietary fat, the same study reported divergent fillet-gaping trends between its two experiments [13]. In salted and vacuum-packed belly flap, shear strength, drip loss, instrumental colour and trained-panel descriptors changed during storage, and sensory findings correlated with physical measurements [18]. These results mean that odour or taste alone does not fully characterize quality: texture, colour, drip and physical integrity are relevant endpoints, and fillet type itself changes the starting material and its response.

Packaging and quality indices

Packaging changes the balance between oxidative and microbial processes rather than uniformly improving every dimension. A controlled fresh-trout study of salting, vacuum packaging and oregano oil reported sensory acceptability of 5 days for the aerobic unsalted control, 8 days for air-packed salted trout, 14 days for salted vacuum-packed trout and 16–17 days for vacuum-packed salted trout with 0.2% oregano oil [19]. In a different experiment on gutted trout at 3°C, modified-atmosphere packaging (MAP1: 40% CO_2/60% N_2; MAP2: 60% CO_2/40% N_2; MAP3: 90% CO_2/10% N_2) delayed sensory/microbial endpoints compared with vacuum packaging; reported sensory-based life was 7 days for vacuum-packed fish, 13 days for MAP1 and MAP2 and 16 days for MAP3 [14]. A separate cold-storage study found that vacuum packaging slowed lipid oxidation relative to air, with lower day-11 TBARS values, while peroxide values were unsuitable as a shelf-life measure because they decompose into secondary products [20]. Vacuum packaging thus limited oxidation compared with air [20], whereas MAP gave longer sensory/microbial life than vacuum in gutted trout [14], because different packaging pairs were compared, neither format can be considered superior independently of the target endpoint and gas composition. Thus, oxygen exclusion can benefit oxidation, while CO_2-rich MAP may better control spoilage organisms in some

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raw-trout protocols; neither format should be treated as universally superior independent of the target outcome and package gas composition (Table 1). Freshness indicators are most informative in combination. TVB-N fluctuated and did not track quality reliably in ice-stored farmed trout [15], in superchilled and chilled trout, TVB-N correlated less strongly with other freshness measures than ATP-related indices [7]. A similar result was reported for the related salmonid Arctic char (*Salvelinus alpinus*) held in ice for 21 days: total volatile nitrogen (15.6–19.8 mg N/100 g) did not increase, whereas the quality index rose linearly with storage time ($R^2 = 0.95$) [21]. Biogenic amines, in contrast, increase with storage and were associated with spoilage organisms and sensory change; putrescine and cadaverine increased especially late in storage [22]. In another ice-storage study, pH and putrescine/cadaverine increased while total volatile bases did not change significantly, leading the authors to propose the amines as quality indicators for that trial [23]. By evaluating kinetic models across −3 to 15°C, a predictive study showed that storage time and temperature drive increases in TVB-N, total viable counts, and amines in both untreated and 1.8% salt-cured fillets [24]. More recently, near-infrared spectroscopy and electronic-nose approaches were associated with TVB-N or volatile-flavour differences and proposed as rapid screening tools, although the abstract does not establish independent external validation [25].

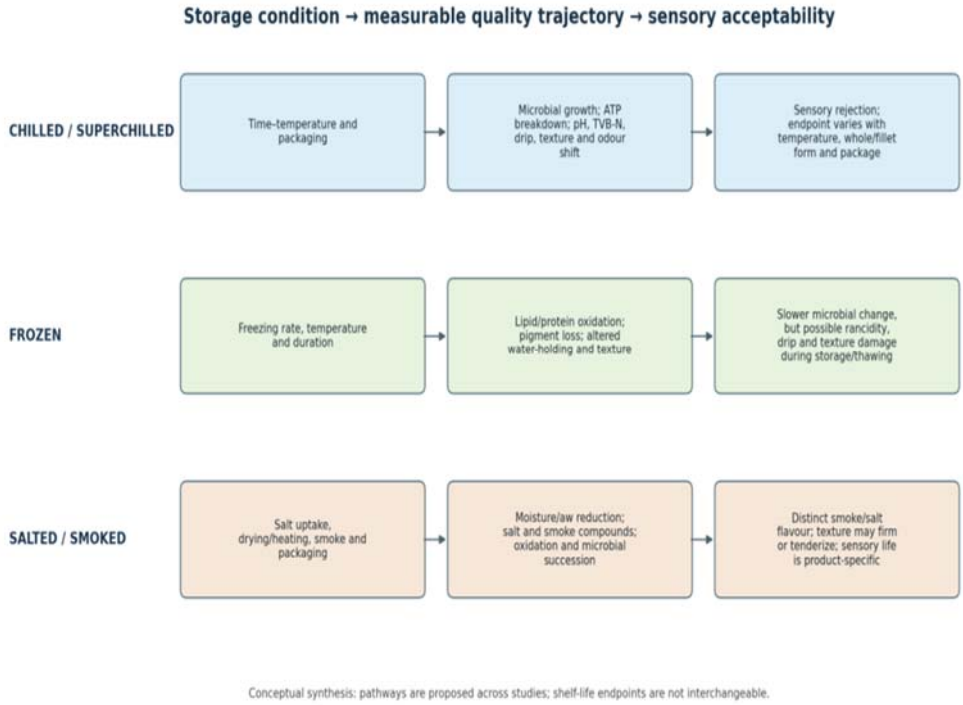


Figure 1. Conceptual overview of how chilled, frozen, salted and smoked storage conditions influence measurable quality changes and sensory acceptance in rainbow trout. Shelf-life endpoints differ between studies and are not interchangeable.

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Table 1 Chilled and superchilled storage of rainbow trout, including lightly salted fillets

Product and storage conditions	Reported results	References
Farmed whole trout on ice, 0–20 d	Sensory/microbial shelf life about 9–11 d; TVB-N fluctuated and was unreliable alone	[15]
Whole ungutted trout vs. fillets on ice	Sensory/microbial life 15–16 d (whole) vs. 10–12 d (fillets); fillets had higher microbial and chemical spoilage indicators	[5]
Gutted vs. ungutted trout, ice storage (commercial case study)	Lower quality-index scores (fresher fish) in gutted trout; maximum life 3 weeks gutted vs 2 weeks ungutted	[6]
Ungutted trout (n = 36) on ice at 0.6–0.8°C, 21 d; QIM (farmed-salmon scheme), five trained panellists	Quality index rose linearly (R^2 = 0.966), 15.3 at day 14; rejection proposed at 15 demerit points or 14 ± 2 d	[4]
Fillets at −3°C (super chilled) or 3°C (chilled)	Composite acceptability limit 11 d at −3°C vs 5 d at 3°C; TVB-N correlated less with other indices than ATP-related indices	[7]
Fillets at −3 to 9°C	Quality deteriorated faster at higher temperatures	[16]
Fillets at 0°C with chitosan, tea polyphenols and lemon juice vs. 0°C and 4°C controls	Lower pH and TVB-N than controls at day 12	[17]
Trout fed low- or high-fat diets, stored on ice for 11 d	Fillets softened during storage; texture differed with dietary fat; gaping trends diverged between the two experiments	[13]
Salted, vacuum-packed belly flap, 0–1.5°C	Shear strength, drip loss, colour and trained-panel descriptors changed with storage time and correlated with each other	[18]
Fillets at 4°C: salting, vacuum packaging, 0.2% oregano oil	Sensory acceptability 5 d (unsalted aerobic control), 8 d (salted, air), 14 d (salted, vacuum), 16–17 d (salted, vacuum, oregano oil)	[19]
Gutted trout at 3°C: vacuum (VP) vs MAP1 (40% CO_2/60% N2), MAP2 (60/40) and MAP3 (90/10)	Sensory-based life 7 d (VP), 13 d (MAP1, MAP2), 16 d (MAP3); MAP limited TVB-N increase; TBARS lowest in VP and MAP3	[14]
Eviscerated trout, air vs vacuum, 2 ± 2°C, 11 days	Lower day-11 TBA under vacuum; peroxide value unsuitable as a single shelf-life index	[20]
Whole and filleted trout on ice	Biogenic amines (especially putrescine and cadaverine, late in storage) increase with spoilage flora and sensory change; patterns differed by product form	[22]
Trout on ice, sampled daily to day 15	pH, putrescine and cadaverine increased; total volatile bases did not change significantly	[23]
Untreated and 1.8% salt-cured fillets at −3, 3, 9 and 15°C	TVB-N, microbial counts and several amines increase with time and temperature; kinetic models evaluated	[24]
Fillets: NIR, e-nose and SPME-GC-MS	NIR predictions correlated with TVB-N; e-nose patterns discriminated freshness stages	[25]

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Collectively, the raw-trout evidence shows that sensory acceptance is a useful integrative endpoint, while physical, microbial and chemical indices explain different parts of deterioration. Where the QIM was applied, the index increased linearly with storage time in ice and a rejection value of 15 demerit points was proposed for ungutted trout [4], whereas TVB-N did not track storage time in the related Arctic char [21]. The reviewed literature does not support a single universal threshold for TVB-N or peroxides. Therefore, the most reliable operational approach is to combine sensory evaluation with microbiological counts and multiple chemical freshness indicators

Frozen storage

Freezing slows microbial deterioration but may alter the protein, lipid, pigment and water-holding properties that determine texture and sensory quality. In processed trout of two weight categories (up to 500 g and up to 3.5 kg) stored at −18°C for 3 months, malondialdehyde and TVB-N increased significantly in both groups, and colour changes differed between them: the smaller fish became lighter and less yellow, whereas the larger fish became darker, less red and less yellow [8]. In gutted, glazed fish stored for 18 months at −28°C, astaxanthin and α-tocopherol levels fell significantly while TBARS remained limited; the highest TBARS values occurred in fish fed the lowest dietary astaxanthin level (40 mg/kg vs 70 or 100 mg/kg) [26]. In fillets, protein carbonylation was about twice as high at −20°C as at −30°C or −80°C [27]. Because these studies differ in product form, storage duration and diet, they show that storage temperature and duration are central to frozen-storage quality, but not that a single temperature is optimal; “frozen” is not a single treatment. Texture and function are also affected by freezing and thawing. Fillets from farmed trout stored at 4°C for 9 days or at −20°C for 6 months showed protein degradation and changes in solubility, water retention, emulsification, colour and texture; the authors suggested that surplus meat could be used in technological processing for up to 2 days refrigerated or 3 months frozen, with later use in conventional preparation [28]. In fillets held for 3 or 7 days at 4°C and then for 30 days at −25°C, frozen storage reduced raw fillet weight by 3.7% and made the muscle less extensible, and shear force measured perpendicular to the muscle fibres correlated only moderately with sensory hardness ($r = 0.42$) [29]. Results therefore depend on whether texture is measured raw or cooked and on blade orientation relative to the fibres, which limits comparisons among frozen-storage studies. Sensory evaluations show that frozen-storage effects depend on temperature, packaging and thawing. In fillets, oxidation products were highest at −5°C even in short-term storage, while long-term storage at −20°C produced extensive lipid oxidation, toughening, expressible-fluid loss after thawing and pigment fading; sensory scores for texture, colour and flavour agreed with chemical rancidity indices, and carotenoids in vacuum-packed trout lost only 0–2% for up to 6 months at −20 or −80°C [9]. In trout stored at −18°C or −40°C for up to 18 months, slow thawing in air at 5°C caused greater tissue-fluid and lysosomal-enzyme leakage (indicators of membrane damage) than fast thawing in water at 25°C, and sensory evaluation confirmed differences between fish stored at −18°C and −40°C after 18 months [30]. Taken together, these studies indicate that freezing is effective for slowing microbial growth but cannot be treated as a quality-neutral holding step. Evidence for oxidation and protein-related changes is consistent, whereas the sensory result after thawing or further processing depends on freezing temperature, duration, cryoprotection and the product's intended use (Table 2).

Table 2 Frozen storage of rainbow trout

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Product and storage conditions	Results	References
Processed trout, two weight categories (up to 500 g; up to 3.5 kg), n = 15 each; −18°C, 3 months	MDA and TVB-N increased significantly in both groups; smaller fish lighter and less yellow, larger fish darker, less red and less yellow	[8]
Gutted, glazed fish fed diets differing in fat, α-tocopherol and astaxanthin; −28°C, 18 months	Astaxanthin and α-tocopherol declined; TBARS limited, highest at the lowest dietary astaxanthin (40 mg/kg)	[26]
Fillets at −20, −30 and −80°C	Protein carbonylation about 2-fold higher at −20°C than at −30 or −80°C	[27]
Fillets from farmed whole trout, 4°C for 9 d or −20°C for 6 months	Protein degradation; changes in solubility, water retention, emulsification, gelation, colour and texture; suggested processing window up to 2 d chilled or 3 months frozen	[28]
Fillets, 3 or 7 d at 4°C, then 30 d at −25°C	Raw weight loss 3.7%; less extensible; shear force correlated moderately with sensory hardness (r = 0.42)	[29]
Fillets stored at −5°C, −20°C and −80°C; vacuum vs air, illuminated vs dark	Extensive oxidation, toughening, fluid loss and pigment fading at −20°C; sensory texture, colour and flavour agreed with rancidity indices; vacuum-packed carotenoids lost 0–2% in 6 months	[9]
Trout stored at −18 or −40°C for 0–18 months, four thawing treatments	Slow thawing increased tissue-fluid and enzyme leakage; −18°C worse than −40°C after ≥3 months; sensory differences confirmed after 18 months	[30]
Fresh vs frozen (−17°C, 30 d, slow thawing) fish for hot smoking	No effect of freezing on final smoked quality or yield	[31]
Frozen trout muscle with cryoprotectants (thesis)	Sucrose/sorbitol-based cryoprotectants reduced several protein changes; $MgCl_2$ tended to worsen denaturation; poorer texture reported in smoked products from frozen fillets	[32]
Marinated, cooked trout döner kebab, 4°C vs −18°C	−18°C inhibited lipid oxidation and microbial growth more effectively than 4°C	[33]
Trout fillets, chilled vs −20°C, up to 1 year	Frozen storage altered texture and gel properties; protein thermal-denaturation measures stable over one year	[34]

Salting

Salting changes moisture, water activity, salt uptake, texture and flavour before any storage effect is considered. In frozen rainbow trout fillets brined in 8.7% or 17.4% NaCl, brine concentration and brining time changed weight loss, water-phase salt, ash, moisture, shear force and cook yield [10]. Brine concentration and brining time also affect protein solubility and water activity, an 8.7% brine for 90 minutes gave maximum texture development while reaching the water-phase salt content (≥3.5%) required by the US Food and Drug Administration [32]. Direct salting and tumbling/brining comparisons found that direct-salted products reached higher water-phase salt while tumbling followed by brining produced the softest texture [35]. Together, these processing studies show that salt concentration alone is insufficient to predict texture; uptake method, time and whether the product is cooked or smoked matter. Light curing can modestly extend raw-fillet acceptance, but formulations interact. Low-concentration curing with 1.3% salt increased the sensory-acceptable storage interval at 4°C from 8 days in untreated samples to 12 days in salted or salted-plus-sugar samples; cadaverine was lower in treated fillets, and sensory outcomes correlated with several spoilage indicators [11]. Dry curing with 1.8% salt, however, did not significantly change TVB-N, total viable counts or

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biogenic amines relative to controls in another temperature-focused study, illustrating that salting effects are not automatic across dose and design [24]. In salted fillets supplemented with thyme oil, TVB-N and bacterial counts were lower in some treatment groups, while sensory acceptability persisted to the study's final 21-day point [36]. In salted fillets at 4°C, 0.8% thyme oil gave the highest panel acceptability, although TVB-N and TBARS increased in all groups [37]. Salt combined with vacuum packaging and onion extract similarly slowed increases in TVB-N and free fatty acids and extended acceptability over the tested period [38].

These are evidence for specific hurdle combinations, not for a universal shelf-life gain from salt alone. Gravad curing (salt and sugar) of raw fillets produces a distinct product state. Vacuum-packed gravad stored at 3°C had an 8-week sensory shelf life in one comparison, while vacuum-packed product at −30°C retained sensory quality beyond 6 months; the authors identified lipid changes as an important limit to chilled storage [39]. Microscopy and texture studies found a more compact gravad structure than in raw trout and increased cohesiveness and chewiness, with further hardness and chewiness changes during storage [40]. This illustrates the dual role of curing: it is a preservation treatment and a textural transformation, so “fresh trout” benchmarks are not transferable to cured products (Table 3).

Smoking, packaging and sensory quality

Smoking causes water loss and concentration of solids while creating the characteristic colour, aroma and flavour. In hot-smoked fillets vacuum-packed at 2°C, a study reported that sensory change was limited through 120 days, with TVN remaining below the study's stated limit; malonaldehyde and microbial counts increased toward the end of storage [41]. In the companion study, redness remained relatively stable and texture remained satisfactory over 120 days. [42]. Another vacuum-packed hot-smoked study reported sensory rejection at 5 weeks for untreated samples, 6 weeks with garlic oil and 7 weeks with thyme oil at 2°C [43]. Cold-smoked sliced fillets (29°C for 24 h) showed a different profile: sensory quality was better in MAP than vacuum packaging, and microbial counts in vacuum packs exceeded 6 log CFU/g after 60 days; TVB-N, already 32.9 mg N/100 g at day 0, approached the study's limit of 40 mg N/100 g by day 45, and TBARS reached 10.6 nmol/g at day 60; the products packed under vacuum or in 70% N_2/30% CO_2 and stored at 4±2°C for 60 days, and the sensory result came from 12 non-professional assessors [12]. These results cannot be ranked directly because smoking method, package gas, product slicing, temperature and rejection criteria differ. Over a 30-day storage period at 2–4°C, traditionally hot-smoked whole rainbow and brook trout (dry-salted for 16 h and smoked at 70–85°C for up to 2 h) exhibited stable pH values (6.2–6.4) and an increase in TVB-N from 10.5 to 19.5 mg/100 g, independent of whether they were stored unpacked, vacuum-packed, in fir branches, or in glass jars. Total aerobic mesophilic counts decreased from an initial level of approximately 10^5 CFU/g, while E. coli remained under 10 CFU/g. No *Salmonella, Yersinia, Listeria monocytogenes*, benzo[a]pyrene, or five other tested PAHs were detected.; the products were judged safe for at least 30 days, but sensory quality was not assessed [1]. Packaging choice remains product-specific. In hot-smoked trout (butterfly fillets brined in 15% NaCl for 4 h) stored at 0–2°C for up to 40 days, common packaging was associated with a reported shelf life of 20–30 days, vacuum with 30–40 days and MAP with at least 40 days; MAP (50% N_2/5% O_2/45% CO_2) sensory scores, given by nine trained panellists, were higher in that study; the TVB-N limit applied was 35 mg N/100 g and peroxide values stayed below 5 meq/kg fat in all packages [3]. In a separate evaluation of cold-smoked samples, a sensory panel observed declines in smoke intensity, colour intensity, and overall acceptability over a six-week period, whereas tenderness remained relatively stable. Across the storage period,

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modified atmosphere packaging (MAP) yielded higher mean sensory scores than vacuum packaging [44]. For vacuum-packed hot-smoked products, a more recent investigation found shelf-life estimates that differed between smokehouses and fell sharply when temperature increase from 2°C to 7.9°C (approximately 100 days versus 45 days at the two temperatures, with variation by smokehouse [45]. The latter finding makes clear that the process environment and cold-chain temperature can be as consequential as the nominal label "hot-smoked. Several studies tested natural antimicrobials, coatings and packaging in smoked trout. In vacuum-packed liquid-smoked fillets, thyme oil extended acceptable life from 105 days in the control to 135 and 150 days at the lower and higher concentrations [46], and a higher brining treatment extended the shelf life of vacuum-packed liquid- and traditionally smoked fillets from 90 to 120 days [47]. Essential oils extended the sensory acceptability of vacuum-packed smoked fillets beyond the 56 days of the control [48], and thyme was reported to be especially effective in hot-smoked trout under vacuum or MAP [49]. Propolis (1%) gave favourable sensory characteristics, whereas 3% delayed spoilage but impaired odour and taste [50], and chitosan coatings enriched with thyme gave the longest shelf life among coating groups [51]. In vacuum-packed hot-smoked fillets (40% brine for 10 min; oak smoke up to 70°C) dipped in olive-oil sauces and stored at 4°C, shelf life based on TVB-N, TBA, microbiological and sensory results was 14 days with olive oil alone, 21 days with thyme, 28 days with garlic and 35 days with garlic plus thyme; TVB-N was 33.2–34.3 mg/100 g at the sampling at which spoilage was detected, thyme-containing sauces limited the rise in TBA, and the garlic-plus-thyme sauce was liked most [2]. Hot-smoked trout with different salt concentrations remained acceptable for up to 45 days under vacuum at 4°C [52]. In liquid-smoked fillets, MAP outperformed vacuum packaging across the tested microbial and chemical indicators [53], and liquid-smoke flavour was associated with 10–20% longer shelf life in ready-to-eat trout and meagre products [54]. Higher doses of additives are therefore not necessarily better, because acceptability and spoilage control can move in opposite directions. Smoking and curing can also bring oxidation and colour changes that are not synonymous with microbial spoilage. Liquid smoking led to progressive increases in lipid hydrolysis and TBARS across processing stages, with lipidomics and flavour-omics profiling pointing to candidate volatile flavour markers. However, the suggested lipid-mediated flavour pathway is currently inferred from correlations and requires direct causal validation [55]. In frozen raw fish and subsequently smoked product, higher α-tocopherol reduced lipid oxidation during chilled storage, while astaxanthin was more relevant to pigment and early oxidation changes [26]. Light exposure and packaging significantly impact quality. Despite high-vacuum sealing, sliced smoked trout displayed under lights faded in colour and developed higher TBARS values than trout kept in the dark [56].

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Table 3 Salting and smoking of rainbow trout

Product and conditions	Reported sensory/physicochemical results	Reference
Brined trout at 8.7% or 17.4% NaCl	Brine concentration altered weight loss, water-phase salt, shear force, moisture and ash.	[10]
Brining time/concentration and muscle functionality	8.7% brine for 90 min produced maximum texture development under the tested procedure.	[32]
Direct salting, brining and vacuum tumbling before smoking	Direct salting produced higher water-phase salt; tumbling then brining produced softer texture.	[35]
1.3% salt with/without 0.9% sugar, 4°C	Sensory acceptance ended at 8 d control and 12 d cured; treated fillets had lower cadaverine at day 8.	[11]
1.8% dry-curing vs. untreated fillets at varied temperatures	Salt treatment did not significantly alter TVB-N, counts or biogenic amines in the abstracted comparison.	[24]
Salted fillets with graded thyme-oil additions, 4°C	Higher thyme-oil treatments remained acceptable to day 21 and had lower TVB-N than salted control.	[36]
Light salt, vacuum and onion extract, refrigerated	Salt/vacuum/extract groups showed lower TVB-N/FFA; treated groups remained acceptable longer than control.	[38]
Salt/sugar gravad, vacuum/air/MAP at 3°C or −30°C	Vacuum-chilled gravad lasted 8 weeks sensorial; frozen vacuum-packed gravad retained sensory quality beyond 6 months.	[39]
Gravad microstructure and texture during storage	Curing compacted muscle structure and increased cohesiveness/chewiness; storage further changed texture.	[40]
Hot-smoked VP fillets at 2°C, up to 120 d	Sensory change was limited; TVN remained below the stated limit, while oxidation and counts increase late.	[41]
Hot-smoked VP fillets with thyme or garlic oil at 2°C	Sensory acceptability: 5 weeks control, 6 weeks garlic and 7 weeks thyme.	[43]
Sliced cold-smoked trout (29°C, 24 h), VP vs. MAP (70% N_2/30% CO_2), 4 ± 2°C, 60 d	Sensory quality favoured MAP (12 non-professional assessors); VP microbial counts exceeded 6 log CFU/g after 60 d; TVB-N about 40 mg N/100 g by day 45.	[12]
Traditionally smoked whole rainbow and brook trout (dry salting 16 h; hot smoke 70–85°C, ≤2 h); unpacked, vacuum, fir branches or glass jars, 2–4°C, 30 d	TVB-N 10.5 → 19.5 mg/100 g, unaffected by packaging; pH 6.2–6.4; TAMB about 10^5CFU/g, decreasing; E. coli <10 CFU/g; *Salmonella, Yersinia, Listeria monocytogenes* and benzo[a]pyrene not detected; sensory quality not assessed.	[1]
Hot-smoked fillets (15% brine, 4 h), common/VP/MAP (50% N_2/5% O_2/45% CO_2) at 0–2°C, 40 d	Reported shelf life was 20–30 d common, 30–40 d VP and at least 40 d MAP; TVB-N limit 35 mg N/100 g; peroxide value < 5 meq/kg.	[3]
Cold-smoked trout, VP vs. two MAP mixtures at 3°C	Sensory scores declined over six weeks; MAP samples had higher average scores and tenderness was stable.	[44]
Hot-smoked vacuum-packed trout from two smokehouses at 2°C/7.9°C	Shelf life varied by smokehouse and temperature, about 100 d at 2°C vs. 45 d at 7.9°C.	[45]
Liquid-smoked trout across salting/smoking stages	Lipid hydrolysis/oxidation increase across stages; volatile flavour markers were identified and a lipid-mediated mechanism proposed.	[55]
Light-exposed vs. dark-stored sliced smoked trout	Light exposure increased paleness and TBARS; packaging did not prevent all lipid oxidation.	[56]

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Product and conditions	Reported sensory/physicochemical results	Reference
Salted and smoked trout after different rigor states	Processing state related to tenderness and salt/water loss; sensory group difference was mainly weaker aroma.	[57]
Liquid-smoked trout with salt/sugar blends, vacuum at 4°C	Brown-sugar group received higher panel scores for appearance, taste, odour and texture.	[58]
Traditional vs. liquid smoke	Both products had high sensory acceptance, with different strengths in appearance/texture and saltiness.	[59]
Traditional vs. liquid smoke, two brining strengths, chilled VP	Reported product shelf life extended from 90 to 120 d with the higher brining treatment in both smoke processes.	[47]
Liquid-smoked VP trout with thyme oil	Reported acceptable lives of 105 d control, 135 d lower thyme and 150 d higher thyme.	[46]
Salted fillets with 0.4%/0.8% thyme oil at 4°C	TVB-N and TBARS increase in all groups; the 0.8% thyme-oil group had the highest panel acceptability.	[37]
Hot-smoked trout at different salt concentrations, VP at 4°C	Lipid-rancidity measures increase while water activity fell; reported sensory/chemical acceptability through 45 d under its protocol.	[52]
Hot-smoked skin-on/skin-off VP fillets at 2°C	Redness remained fairly stable; filleting prevented gaping and texture stayed satisfactory over 120 d.	[42]
Smoked trout made from frozen raw material, chilled display	Fillet α-tocopherol reduced lipid oxidation in smoked product; astaxanthin declined during display.	[26]
Hot-smoked trout with thyme/rosemary oil and VP/MAP	Essential-oil treatments were reported to improve shelf life, especially thyme.	[49]
Vacuum-packed smoked trout with essential oils	Sensory acceptability was reported through 56 d control and longer in rosemary/thyme/sage/clove treatments.	[48]
Hot-smoked VP trout with graded propolis extract at 4°C	1% propolis had favourable sensory characteristics; 3% delayed spoilage but impaired odour/taste.	[50]
Hot-smoked trout with chitosan/essential-oil coatings	Inconsumable endpoints differed among coating groups, with thyme-enriched coating lasting longest.	[51]
Vacuum-packed hot-smoked fillets (40% brine, 10 min; oak smoke up to 70°C) dipped in olive-oil, garlic, thyme or garlic + thyme sauces, 4°C	Shelf life 14, 28, 21 and 35 d, respectively (TVB-N 33.2–34.3 mg/100 g when spoiled); thyme limited the TBA increase; garlic + thyme liked most.	[2]
Liquid-smoked trout, brining and VP/MAP at 4°C	MAP performed better than VP across the tested microbial and chemical indicators.	[53]
Rainbow trout and meagre ready-to-eat salted/smoked products	Liquid smoke flavour was associated with 10–20% longer shelf life in the reported product set.	[54]

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Instrumental colour and sensory outcomes therefore depend on both raw-fish pigment/diet and post-processing storage/display conditions. Consumer response is not a simple proxy for chemical stability. In one lightly salted/smoked product study, sensory evaluation favoured the group processed after rigor resolution except for weaker aroma; thermal shrinkage and tissue damage were associated with appearance, flavour and chewiness changes [57]. A salt-sugar formulation study found that brown-sugar-treated liquid-smoked fillets scored more favourably for appearance, taste, odour and texture despite limited differences among groups in many measured physicochemical variables [58]. Sensory and physicochemical trials comparing traditional smoking with liquid smoke consistently show high consumer acceptance for both methods, though distinct trade-offs emerge regarding texture, appearance, and flavour perception [59]. Smoke intensity, saltiness, tenderness and appearance can thus be desirable product attributes in their own right, not simply indicators of spoilage.

Synthesizing the available literature indicates that the efficacy of salting and smoking relies on hurdle technology, combining osmotic dehydration, thermal or chemical smoke effects, barrier packaging, and supplementary preservatives. Despite extending microbiological stability, these interventions shows sensory trade-offs. Salt can improve keeping quality while shifting saltiness and texture; smoking can reduce moisture and add desirable flavour but may also intensify oxidation or produce texture changes.

CONCLUSIONS

Rainbow trout quality declines through interacting microbial, enzymatic, oxidative and structural changes, and its sensory expression depends on product form and preservation method.

The synthesis of current literature indicates that low-temperature storage governs spoilage kinetics through distinct mechanisms: while chilling and superchilling primarily attenuate deterioration rates, freezing arrests microbial proliferation yet remains susceptible to lipid oxidation, protein denaturation, pigment degradation, and textural loss. Conversely, salting and smoking impart desirable sensorial attributes and extend shelf life across diverse formulations, though their efficacy remains heavily contingent upon processing intensity, packaging, temperature, and matrix composition. Consequently, sensory acceptability must be evaluated concurrently with microbiological and physicochemical indices, preserving study-specific rejection thresholds rather than relying on pooled benchmarks. Ultimately, trout preservation is best conceptualized as a targeted hurdle-design challenge, wherein optimal conditions balance the suppression of product-specific spoilage pathways against the retention of desired sensory qualities.

Studies rarely use common endpoints or thresholds, so shelf-life values cannot be compared across product forms; panel type and chemical limits also differ, and standardised sensory methods validated against microbial and chemical indices are needed.

While existing research focuses primarily on general quality parameters, crucial food-safety hazards (*Listeria monocytogenes, Clostridium botulinum type* E, and polycyclic aromatic hydrocarbons) and fatty acid profile alterations in vacuum-packed and smoked trout remain underexplored and require future research.

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