Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal

Cite this: DOI: 10.1039/d5fb00404g

Vitamin D biofortification of salmon (*Salmo salar*) processing offcuts to create novel shelf-stable foods

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Received 21st July 2025
Accepted 22nd November 2025

DOI: 10.1039/d5fb00404g

rsc.li/susfoodtech

The utilisation of edible seafood processing waste could be beneficial for environmental, economic and health outcomes. We developed a method to rapidly enhance the vitamin D content of shelf-stable snacks made from salmon (*Salmo salar*) processing offcuts. Raw salmon skin, crispy salmon skin snacks and salmon jerky were treated with pulsed ultraviolet light, and vitamin D_3, 25-hydroxyvitamin D_3 (25(OH)D_3), vitamin D_2 and 25(OH)D_2 concentrations were measured before and after treatment. Ultraviolet light treatment increased vitamin D_3 in raw salmon skin and crispy salmon skin snacks by a mean (SD) of 53.6 (12.3) and 48.7 (1.8) μg/100 g, respectively. Crispy salmon skin snacks and salmon jerky contained 1.1 (0.1) and 1.6 (0.02) g/100 g omega-3 long-chain polyunsaturated fatty acids, respectively. Pulsed ultraviolet light could be a commercially viable method for producing nutrient-dense, novel foods that can be made from seafood processing offcuts.

Sustainability spotlight

There is a critical need to make efficient and sustainable use of precious ocean resources, while production of nutrient-rich foods is needed to support growing populations. Our work to support the utilisation of potential food waste products aligns strongly with Sustainable Development Goal (SDG) 12, to "ensure sustainable consumption and production patterns", while the recovery of nutrient-rich and food safe fish by-products relates to SDG 2 for its potential to improve nutrition. This study also aligns with SDG 14 in terms of more sustainable use of ocean resources.

Introduction

More than a third of the global fish harvest is discarded as waste,[1] and 70% of some seafood is discarded during processing.[2,3] There are environmental concerns around the disposal of seafood waste into oceans and landfills,[4,5] while food security is an important consideration now and for the future.[6] Some seafood by-products are used in industrial applications, such as livestock feed and aquaculture; however, their recovery and utilisation for human consumption may offer greater potential by contributing to sustainability, environmental and economic benefits, food security, and improved health outcomes.[2,7,8] To ensure a sustainable future, it is imperative to produce food resources more responsibly, use ocean resources more sustainably and generate highly nutritious food products for the growing population.[9,10] This would align with Sustainable Development Goals (SDGs) 2, 12 and 14 that relate to addressing the global issue of hunger and food insecurity, ensuring sustainable consumption and production patterns, and conserving and sustainably using ocean sea and marine resources.[11]

The challenge in marketing food-safe matter that is discarded during seafood processing is its aesthetic appeal to consumers.[9] If the marine food industry can overcome this cosmetic issue by creating novel food products with greater consumer appeal, marine food processing by-products represent a valuable opportunity for environmental, economic and nutritional gain. This could include improved access to nutrient-rich foods such as those enriched with vitamin D and omega-3 long-chain polyunsaturated fatty acids (LCPUFAs).

Low vitamin D status is common, with an estimated global prevalence of circulating 25-hydroxyvitamin D concentration < 50 nmol L^{-1} of nearly 50%.[12] Along with its crucial role in bone health, vitamin D may lower the risk of respiratory tract

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infections, adverse pregnancy outcomes, developing type 2 diabetes, and mortality in older adults.[13] Omega-3 LCPUFAs are associated with numerous health benefits across the life course, including reduced all-cause mortality, cardiovascular risk, risk of preterm birth, and inflammation, as well as improved brain and eye health.[14] Despite these well documented health benefits, omega-3 LCPUFA intake remains low among most populations, with omega-3 index levels, a biomarker of omega-3 LCPUFA status, classified as low to very low in many countries.[14]

Atlantic salmon (*Salmo salar*) is a valuable natural food source of vitamin D[15] and omega-3 LCPUFAs.[16] However, filleting plants in the Atlantic region have been estimated to produce 30–60% solid waste[7] at great commercial and nutritional loss of vitamin D- and omega-3 LCPUFA-rich edible offcuts. Making more efficient use of seafood by-products, including fish heads, viscera, bones, scales and skin has been the subject of a number of recent reviews, underscoring the topical and expanding nature of this research field.[17–19] The valorisation methods discussed commonly include the extraction of bioactive compounds, such as collagen, peptides, fatty acids, minerals and antioxidants through enzymatic hydrolysis and other chemical or physical processes, with applications in food, nutraceutical and cosmetic industries.[17–19] While these approaches contribute to waste reduction, most do not fully align with SDG 12.3, which calls for halving global food waste and returning at least 50% of material losses back into the supply chain.[11,20] True alignment with SDG 12.3 therefore requires full or near-complete utilisation of seafood by-products through integrated bioprocessing and closed-loop system design, ensuring the generated products re-enter the food or feed value chain, rather than being diverted to lower-value or non-food applications.

Valorisation of fish processing offcuts has also been explored through treatment with ultraviolet (UV) light to enhance vitamin D content. Recently, Atlantic salmon (*Salmo salar*) kept in indoor holding tanks and continuously exposed to UV-B light for 4 weeks were found to contain 2.5–6 times more vitamin D_3 compared to fish continuously exposed to standard light; the difference in vitamin D_3 concentration was >5 times higher in UV-B exposed fish after ~10 weeks of exposure.[21] Furthermore, it has been shown that the vitamin D_3 content of foods that contain a vitamin D precursor may be increased after cooking. A Danish team increased the vitamin D_3 content of cooked pork crackling to ~10 μg/100 g through exposure under a UV-B lamp.[22] We hypothesised that there would be similar potential to enhance the vitamin D content of cooked salmon products to create a vitamin D-rich food source using pulsed UV light, which has already been used to vastly and rapidly (within seconds) enhance the vitamin D content of dried and cooked mushrooms.[23–25]

Our research team has developed shelf-stable salmon skin snacks and jerky that can be made from salmon (*Salmo salar*) processing offcuts (skin and minced flesh). Similar value-adding applications of salmon by-products are already established commercially.[26,27] In this study, we aimed to develop a method to rapidly enhance the vitamin D content of raw salmon skin and shelf-stable crispy salmon skin snacks and salmon jerky that can be made from salmon processing offcuts. A secondary aim was to explore whether a nutritionally meaningful fatty acid content, in particular omega-3 LCPUFA content, remained in the crispy salmon skin snacks and salmon jerky post treatment.

Methods

Fresh farmed Tasmanian Atlantic salmon (*Salmo salar*) skin and flesh were purchased from a seafood wholesaler in Bayswater, Western Australia, on 11th September 2023. Samples were transported (~30 minutes) to Curtin University, Bentley, Western Australia and prepared immediately.

Sample purchase, preparation and pulsed UV treatment

Raw salmon skin. Approximately 25 half salmon skins were descaled and any attached flesh was removed (remaining wet weight = 1.546 kg). Skins were cut into ~3 × 3 cm pieces. Six aliquots (32–33 g each) of skin were set aside for analysis in the raw form. Three of these samples were packaged (wrapped in foil, labelled, and sealed within a labelled zip-lock bag) and frozen at −18 °C immediately. Three further aliquots (31–37 g each) of average thickness 0.71 mm (average of three caliper readings [0–150 mm rating stainless hardened digital calliper, RS Pro, Smithfield, New South Wales, Australia]) were placed skin-side up under a pulsed xenon lamp (Wek-tec XematicA-2L, Wek-tec e. K., Gottmadingen, Germany) and treated with three pulses of UV light (260–800 nm) before being packaged and frozen. The distance from the sample tray to the lamp was 13.2 cm. The average UV dose and peak per pulse was calculated as the average of 10 calibration pulses (five before and five after sample treatment). The average dose per pulse, as measured using a radiometer (ILT800 CureRight, International Light Technologies, Peabody, MA, USA; measurement range 215–350 nm), was 34.72 mJ cm^{-2} with an average peak of 15.01 W cm^{-2} (Table 1). The remaining 1.350 kg skin was vacuum packed and refrigerated at 4 °C overnight, then processed into shelf-stable crispy salmon skin snacks the next morning.

Crispy salmon skin snacks. Crispy salmon skin snacks (ingredient percentages: 82% salmon skin, 15% corn starch, 1.5% olive oil, 1.5% salt) were prepared by coating salmon skin pieces in a mixture of corn starch and salt and sieving to remove excess coating. After coating with olive oil, skin pieces were baked until crispy, allowed to cool and packaged in nitrogen-filled modified atmosphere packaging overnight. Three crispy salmon skin snack samples (30 g each) were packaged and frozen for baseline analysis. Three further samples (50 g each) were treated with three pulses of UV light at 7 V (average dose per pulse 34.63 mJ cm^{-2}, average peak 14.91 W cm^{-2}) before being packaged and frozen.

Salmon jerky. Non-irradiated salmon flesh (2.94 kg) was passed through a mincer (Kenwood Chef A901E, Kenwood Australia, Prestons, New South Wales, Australia) twice, vacuum packed and refrigerated overnight before being processed into salmon jerky the next morning. Salmon jerky was prepared by marinating salmon mince in a brine solution (10% sodium

Table 1 Analytical samples for comparison of vitamin D content before and after pulsed ultraviolet light treatment[a]

Sample	Weight (g)	Thickness[b] (mm)	UV treatment	UV dose[c] (mJ cm^{-2})	UV peak[c] (W cm^{-2})
Salmon (*Salmo salar*)					
Skin, raw		0.71		34.72	15.01
Sample A baseline	32		None		
Sample A UV	31		3 pulses skin side up		
Sample B baseline	32		None		
Sample B UV	31		3 pulses skin side up		
Sample C baseline	33		None		
Sample C UV	37		3 pulses skin side up		
Crispy skin snacks [d]		—		34.63	14.91
Sample A baseline	30		None		
Sample A UV	50		3 pulses skin side up		
Sample B baseline	30		None		
Sample B UV	50		3 pulses skin side up		
Sample C baseline	30		None		
Sample C UV	50		3 pulses skin side up		
Jerky		2.90		34.97	14.98
Sample A baseline	30		None		
Sample A UV	50		3 pulses on each side		
Sample B baseline	30		None		
Sample B UV	50		3 pulses on each side		
Sample C baseline	30		None		
Sample C UV	50		3 pulses on each side		

[a] UV, ultraviolet light. [b] Calculated as the average of three caliper readings. [c] Calculated as the average of 10 calibration pulses – five before and five after sample treatment. [d] Thickness measured in the raw form only – shape did not allow for measurement in the cooked form.

chloride) and adding a binding enzyme. This mixture was refrigerated and allowed to set before being baked until it reached a suitable texture. Average thickness (based on caliper readings from 10 samples) was 2.9 mm. Three salmon jerky samples (30 g each) were packaged and frozen for baseline analysis. Three further samples (50 g each) were treated with three pulses of UV light at 7 V (average dose per pulse 34.97 mJ cm^{-2}, average peak 14.98 W cm^{-2}) before being packaged and frozen.

Sample transport and analysis

Within two weeks of preparation, samples were couriered by overnight service from Curtin University to the National Measurement Institute of Australia (NMI), Port Melbourne, Victoria for nutrient analysis. Samples were packed in an insulated box with sufficient dry ice to last the journey.

Moisture, fat, vitamin D_3, 25(OH)D_3, vitamin D_2 and 25(OH)D_2 were measured in all samples. Fatty acids were measured in the final products, UV-treated crispy salmon skin snacks ($n = 3$) and UV-treated salmon jerky ($n = 3$).

Moisture was measured using an in-house method that was based on a published AOAC method.[28] Total fat was measured using the Soxhlet extraction method.[29]

We used a liquid chromatography with triple quadrupole mass spectrometry (LC-QQQ) method (ISO17025:2017) to measure the four D vitamers – a method that has been described in detail elsewhere.[15,30–32] In brief, sufficient sample to yield $\leq$ 1 g saponified fat was combined in a 50 mL Falcon® tube with a known amount of chemically labelled internal standard, 1 g sodium ascorbate, 10 mL deionised water, 30 mL ethanol (100%), 2 g potassium hydroxide pellets (85% purity), and deionized water to make 50 mL. The mixture was saponified overnight in a shaker bath. It was then hydrolysed in the resulting ethanolic potassium hydroxide solution and the D vitamer analytes were extracted to diatomaceous earth solid phase extraction tubes. Petroleum spirit (40–60 °C) was used to wash the D vitamer analytes through the extraction tubes.

The washes were evaporated to dryness under nitrogen gas. The residues were redissolved in heptane and evaporated to dryness again using nitrogen gas; they were then redissolved in 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD) in anhydrous acetonitrile for derivatisation, which was halted after 10 minutes by addition of water. The D vitamer analytes were isolated using a reverse phase C18 column (Supelco Ascentis® Express C18, 15 cm $\times$ 3 mm, 2.7 μm [Cat # 53816-U]) and analysed using an LC-QQQ (1290 Infinity Series LC System and 6460 Triple Quad LC-MS, Agilent Technologies, Santa Clara, USA) along with a range of calibration samples. The system was set up in electrospray ionization mode with positive polarity. D vitamer analyte concentrations were determined using a calibration curve.

Fatty acid profiling (saturated, monounsaturated and polyunsaturated fatty acids) was conducted using gas chromatography-flame ionization detection (GC-FID).[33–35]

Quality assurance and data handling

All analyses were conducted in duplicate and the relative percent difference (RPD) between replicated analyses was calculated as: (difference between duplicated analyses/average of duplicated analyses) $\times$ 100. Recovery analysis was conducted in three samples chosen at random by adding a known concentration (μg/100 g of sample matrix) of each D-vitamer.

The recovery percentage was reported based on the concentrations measured in spiked samples. The limits of reporting for moisture, fat, D vitamers and the proportion of fatty acid fractions (total saturated, total polyunsaturated, total omega-6) were 0.1 g/100 g, 0.2 g/100 g, 0.5 μg/100 g and 0.1%, respectively. The mean value per nutrient was calculated as the average of duplicated results for each sample. For selected fatty acids, content (g/100 g) was derived from fat content and percentage of total fatty acid content using a factor of 0.9 to account for non-fat components of triglycerides in fatty fish.[36] A paired *t*-test was used to test for differences between D vitamer content before and after treatment. Statistical significance was considered as $p < 0.05$. Statistical tests were conducted using Stata 15.[37]

Results and discussion

The mean RPD was 16% for vitamin D_3 and 0% for 25(OH)D_3, vitamin D_2 and 25(OH)D_2. Recovery of known concentrations from spiked samples ranged from 76 to 115%. For total saturated, total polyunsaturated and total omega-6 fatty acids, the mean RPD was 1.2, 0.5 and 0.6%, respectively.

At baseline, the mean (SD) concentration of vitamin D_3 in raw salmon skin, crispy salmon skin snacks and salmon jerky was 0.7 (0.1), 0.7 (0.03) and 0.7 (0.05) μg/100 g, respectively. There was a statistically significant increase in vitamin D_3 following pulsed UV light treatment in all three products. In raw salmon skin, crispy salmon skin snacks and salmon jerky, the respective mean (SD) increases in vitamin D_3 in these products were: 53.6 (12.3), $p = 0.0001$; 48.7 (1.8), $p = <0.0001$; and 1.7 (0.3), $p = 0.0001$ μg/100 g (Table 2).

Selected fatty acid profiles of the crispy salmon skin snacks and salmon jerky treated with pulsed ultraviolet light are summarised in Table 3, with the full fatty acid analysis available in SI Table 1. The crispy salmon skin snacks contained a mean (SD) of 1.1 (0.1) g/100 g omega-3 LCPUFAs, while the salmon jerky contained 1.6 (0.02) g/100 g.

We enhanced the vitamin D content of novel shelf-stable food products made from salmon skin and flesh using pulsed UV light. We also demonstrated that these snacks are valuable sources of omega-3 LCPUFAs.

For crispy salmon skin snacks, the serving size for a comparable commercially available product is suggested as 28 g.[26] A 28 g serving of our vitamin D-enhanced crispy salmon skin snacks would provide ~14 μg vitamin D_3, which is almost equal to the Recommended Dietary Allowance of 15 μg recommended by the Institute of Medicine for people aged up to 70 years.[38] A comparable commercially available salmon jerky product is sold in a single-serve sized bag of 30 g.[27] A 30 g serving of our vitamin D-enhanced salmon jerky would provide <1 μg vitamin D_3. The smaller increase in vitamin D_3 in salmon jerky compared to salmon skin may be due to the greater thickness of the jerky product, or the skin being the primary site of vitamin D_3 production (with a higher concentration of 7-dehydrocholesterol). Future studies could experiment with application of different doses of UV light to achieve different concentrations of vitamin D_3 in products made from salmon skin and flesh.

Our salmon-derived snack products contained nutritionally useful amounts of LCPUFAs. A 28 g serving of our crispy salmon skin snacks would provide 0.3 g of omega-3 LCPUFAs, while a 30 g serving of salmon jerky would provide 0.5 g. Current recommendations for omega-3 LCPUFAs (combined eicosapentaenoic acid [EPA] and docosahexaenoic acid [DHA]) range from 250–500 mg per day for general health, and up to 1 g per day for individuals with heart failure.[39,40] However, there is concern that these levels may be insufficient to achieve optimal omega-3 index targets,[41] further challenging adequate intake. These salmon-based snacks made from offcuts may help

Table 2 Moisture, fat and D vitamer composition of salmon products before and after treatment with pulsed ultraviolet (UV) light[a]

		Moisture g/100 g	Fat g/100 g	Vitamin D_3 μg/100 g	25(OH)D_3 μg/100 g	Vitamin D_2 μg/100 g	25(OH)D_2 μg/100 g
Salmon skin, raw	Sample A baseline	63.8	7.9	0.7	<0.1	<0.1	<0.1
	Sample A UV	63.1	3.9	41.5	<0.1	0.1	<0.1
	Sample B baseline	64.9	6.3	0.7	<0.1	<0.1	<0.1
	Sample B UV	63.8	5.3	66.0	<0.1	<0.1	<0.1
	Sample C baseline	60.8	7.2	0.9	<0.1	<0.1	<0.1
	Sample C UV	61.8	7.4	55.5	<0.1	0.1	<0.1
Crispy salmon skin snack	Sample A baseline	5.2	15.7	0.7	<0.1	<0.1	<0.1
	Sample A UV	4.6	16.9	47.5	<0.1	0.3	<0.1
	Sample B baseline	4.9	16.5	0.7	<0.1	<0.1	<0.1
	Sample B UV	4.3	18.0	49.5	<0.1	0.4	<0.1
	Sample C baseline	5.1	20.5	0.7	<0.1	<0.1	<0.1
	Sample C UV	4.1	19.8	51.0	<0.1	0.35	<0.1
Salmon jerky	Sample A baseline	23.1	19.5	0.7	<0.1	<0.1	<0.1
	Sample A UV	24.0	18.6	2.8	0.1	<0.1	<0.1
	Sample B baseline	28.4	19.0	0.8	<0.1	<0.1	<0.1
	Sample B UV	25.6	18.7	2.2	0.1	<0.1	<0.1
	Sample C baseline	26.3	20.1	0.7	<0.1	<0.1	<0.1
	Sample C UV	24.8	19.2	2.3	<0.1	<0.1	<0.1

[a] 25(OH)D, 25-hydroxyvitamin D.

Table 3 Selected fatty acids content of crispy salmon skin snacks and salmon jerky treated with pulsed ultraviolet light[a]

	Crispy salmon skin snacks ($n = 3$)				Salmon jerky ($n = 3$)			
	% of total		g/100 g		% of total		g/100 g	
Fatty acid	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C16:0 palmitic acid	11.1	0.2	1.8	0.1	9.4	0.1	1.6	0.0
C18:0 stearic acid	3.4	0.0	0.6	0.0	3.2	0.0	0.6	0.0
Total SFAs	16.4	0.1	2.7	0.2	15.0	0.1	2.8	0.0
C18:1 oleic acid	50.7	0.6	8.3	0.7	43.4	0.1	8.2	0.1
Total MUFAs	56.9	0.6	9.3	0.7	51.1	0.2	9.6	0.1
C18:2 omega-6 linoleic acid	13.2	0.3	2.2	0.2	16.5	0.0	3.1	0.0
C18:3 omega-3 alpha-linolenic acid	4.1	0.2	0.7	0.1	6.0	0.1	1.1	0.0
C20:5 omega-3 eicosapentaenoic acid	1.6	0.1	0.3	0.0	1.6	0.0	0.3	0.0
C22:5 omega-3 docosapentaenoic acid	0.6	0.0	0.1	0.0	0.9	0.2	0.2	0.0
C22:6 omega-3 docosahexaenoic acid	4.5	0.2	0.7	0.1	5.6	0.1	1.1	0.0
Total PUFAs	26.3	0.6	4.3	0.3	33.5	0.3	6.3	0.1
Total omega-3 LCPUFAs	7.0	0.3	1.1	0.1	8.5	0.2	1.6	0.0

[a] LCPUFAs, long-chain polyunsaturated fatty acids; MUFAs, monounsaturated fatty acids; PUFAs, polyunsaturated fatty acids; SFAs, saturated fatty acids.

consumers meet their daily omega-3 LCPUFA intake targets by expanding the range of omega-3 LCPUFA-containing food options. Future studies could include measurement of fatty acids throughout the production process. This would allow comparison of fatty acid content in the raw product and before and after pulsed UV light treatment to determine whether fatty acid oxidative stability and content are affected by the pulsed UV treatment or preparation processes; heat-producing processes such as baking may promote omega-3 LCPUFA oxidation,[42] while vacuum packing may protect against oxidation by reducing oxygen exposure.[43]

It was not possible to quantitatively compare our findings with other studies, or indeed findings between other studies, due to differences in fish species examined, treatment conditions (live fish *vs.* post processing/cooked products), and varied UV exposure protocols. Nevertheless, our finding that the vitamin D content of fish products can be augmented through treatment with UV light aligns qualitatively with previous research, consistently showing an increasing trend in vitamin D_3 content following UV-B exposure. Our finding supports the hypothesis of the authors of a recent publication that UV-B radiation could be a key source of vitamin D_3 synthesis in farmed salmon, given common production conditions of relatively shallow, outdoor cages with natural exposure to UV-B light.[21] In that team's study, Atlantic salmon fillets from farmed fish continuously exposed to UV-B light for ~10 weeks contained ~4–5 μg/100 g vitamin D_3, compared to <1 μg/100 g in fillets from fish continuously exposed to standard light over the same time period.[21]

The effect of treating other fish species with UV light has been explored in other studies. In an early study, published in 1997, two groups of Tilapia (*Tilapia mossambica*, unreported whether of farmed or wild origin) were kept in plastic pools in darkness for one week and fed a vitamin D-free diet.[44] Thereafter, a 30 W UV lamp was lit above one pool for 15 h. The UV-treated whole fish contained ~16 μg/100 g higher vitamin D_3 compared to the control group (kept in darkness).[44] In a more recent study published in 2024, wild-caught samples of mackerel (*Scomber scombrus*), bluefish anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*), red mullet (*Mullus barbatus*) and European hake (*Merluccius merluccius*) were treated under a UV lamp for 30–90 minutes, resulting in vitamin D_3 levels >10 times greater than those before UV light treatment.[45] The potential for vitamin D augmentation *via* UV light treatment may differ by species, depending on skin thickness or 7-dehydrocholesterol content.[45] While more studies are needed to establish more directly comparable data, these collective findings show that the use of UV-B light to increase the vitamin D content of fish products has been consistently successful across multiple species and experimental contexts.

The mechanism by which UV light increases vitamin D in fish is thought to be analogous to the process that occurs in humans and other mammals.[21,45] In humans, exposure of skin to UV-B radiation (either *via* sunlight or a UV lamp) induces the photochemical conversion of the cutaneous provitamin 7-dehydrocholesterol to previtamin D_3.[46] Subsequently, previtamin D_3 thermally isomerises to form vitamin D_3.[46]

Although existing studies are not directly comparable, the remarkably higher vitamin D_3 levels observed in salmon skin relative to the previously reported concentrations in salmon flesh[21] suggest that, in *Salmo salar*, vitamin D_3 biosynthesis may predominantly occur within the cutaneous layer, a hypothesis supported by evidence of cutaneous vitamin D_3 formation in other salmonoids.[47] This highlights the need for targeted comparative studies investigating vitamin D_3 accumulation between the skin and flesh within the same cohort. Importantly, these findings suggest that salmon skin, typically discarded during processing, could serve as a valuable substrate for vitamin D_3 enrichment and recovery for human nutrition. Further investigation into dose-dependent kinetics and spatial localization of vitamin D_3 synthesis within fish tissues is warranted, particularly to optimise UV exposure regimes that

maximise vitamin D_3 formation while preserving the nutritional and sensory quality of the product.

While the current evidence is insufficient to determine whether standard pulsed UV light is more energetically efficient than continuous UV lamp exposure, pulsed UV light offers substantial operational advantages. The process can achieve a significant increase in vitamin D content within seconds, compared to the extended exposure periods (hours to weeks) required for standard UV lamps. Pulsed UV light is, therefore, a more spatially and temporally efficient approach that avoids prolonged housing of live animals or products under irradiation.

Future work could assess whether end-product quality (*e.g.*, organoleptic properties, colour, texture, and nutrient composition) is influenced by UV dose intensity and exposure regimen, such as extended standard UV lamp exposure *versus* varying intensities and frequencies of pulsed UV delivery.

In addition to increasing vitamin D_3 levels, UV-B irradiation may also confer microbiological safety benefits by reducing surface microbial loads responsible for spoilage and foodborne risk.[48,49] This dual functionality suggests that UV-B treatment could partially replace or complement conventional sanitisation methods, which often rely on chemical disinfectants containing potentially carcinogenic compounds.[50] Unlike these chemical agents, UV-B acts through a photo-oxidative mechanism, which can simultaneously facilitate vitamin D_3 synthesis and microbial inactivation, thereby reducing overall chemical usage during processing.

It is, however, unknown whether there is a pulsed UV light dose at which vitamin D_3 begins to degrade, either through photo-degradation[51] or due to heat generated by the UV lamp.[22] Similarly, it is unknown how other components may be affected by varying doses and methods of delivery of UV light. UV irradiation may affect protein content or structure *via* damage to DNA.[52] In peanuts exposed to UV light over several days, fatty acid content was not significantly affected; however, oxidation of tocopherols had begun at 3 days of exposure and the content of aldehydes had increased by >8 and >11 times at 3 and 7 days of exposure, respectively.[53] The effect of UV irradiation on such components in our salmon snacks requires further study.

Our current focus was to establish a method to augment vitamin D content while ensuring nutritional integrity of omega-3 fatty acids. Future studies could investigate the rancidity and oxidative stability of UV-treated fish products over time, using parameters such as thiobarbituric acid reactive substances (TBARS), total volatile basic nitrogen (TVB-N), acidity value, and peroxide/oxidation value, to comprehensively evaluate product quality and safety during storage. It is necessary to determine the optimal UV-B dose range that maximises microbial safety and vitamin D_3 formation while minimising any unwanted oxidative degradation. Additionally, future research could include consumer acceptance, sensory evaluation, and recipe refinement of the crispy salmon skin snacks and salmon jerky, along with other products developed from nutrient-rich offcuts. Potential marketing strategies for such foods could be informed by exploring consumer attitudes towards concepts that could be used to market nutrient-dense novel foods made from processing by-products.

A strength of our study was the use of a pulsed UV light method that increases the vitamin D content of foods in seconds. We used a sensitive and specific assay to measure concentrations of vitamin D_3, 25(OH)D_3, vitamin D_2 and 25(OH)D_2. A limitation was that the scope of this study was constrained by resourcing, limiting the number of samples that could be included. While we were able to demonstrate a consistent increase in vitamin D_3 following pulsed UV light treatment across a number of samples of two different products, fatty acid profiling was conducted after, but not before, UV light treatment. Our findings indicate that a larger study is warranted, including a larger number of samples and experimenting with different doses of pulsed UV light to ascertain how vitamin D_3 content, and that of other key nutrients (such as individual amino acids and overall protein content), is affected.

Conclusions

In this study, we found that the application of pulsed UV light caused a rapid increase in the vitamin D_3 content of raw salmon skin, crispy salmon skin snacks and salmon jerky. The increase was particularly pronounced in raw salmon skin and crispy salmon skin snacks. Pulsed UV light-treated salmon snacks could also serve as valuable sources of omega-3 LCPUFAs, offering consumers a novel dietary option to help increase their intake of these important fatty acids. This study provides a commercially viable method for producing nutrient-dense, shelf-stable snack products that can be made from seafood processing offcuts. The findings indicate that further research is warranted to investigate the application of pulsed UV light in larger samples of salmon-based snacks, and to explore the effect of treatment on other nutrient components, food safety indicators and consumer acceptance.

Author contributions

Eleanor Dunlop: conceptualization, funding acquisition, methodology, investigation, data curation, project administration, writing – original draft. Alexis Wing Huen Chung: methodology, investigation, writing – review and editing. Janet Howieson: conceptualization, methodology, supervision, writing – original draft. Belinda Neo: investigation, writing – review and editing. Welma Stonehouse: data curation, writing – original draft. Paul Adorno: resources, writing – review and editing. Georgios Dabos: methodology, investigation, writing – review and editing. Linda Portsmouth: funding acquisition, methodology, writing – review and editing. Lucinda J. Black: conceptualization, funding acquisition, methodology, writing – review and editing.

Conflicts of interest

Eleanor Dunlop reports a relationship with dsm-firmenich that includes receipt of grant funding and travel reimbursement within the past five years. Lucinda Black reports a relationship

with dsm-firmenich that includes receipt of grant funding within the past five years. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data supporting this article (full fatty acid profiling results) have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5fb00404g.

Acknowledgements

This research was supported by Curtin University's School of Population Health. BN is supported by an Australian Government Research Training Program Scholarship.

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