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Sustainable valorization of yellow nectarine peel through green extraction technologies: Recovery of bioactive compounds and storage stability assessment

Bhuyashi Boruah[1]
Subhajit Ray[2+]

[1,2]*Department of Food Engineering and Technology, Central Institute of Technology Kokrajhar, Kokrajhar, BTAD, Assam, 783370, India.*
[1]*Email: ph23fet1001@cit.ac.in*
[2]*Email: subhajit@cit.ac.in*

(+ Corresponding author)

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ABSTRACT

Yellow nectarine (Prunus persica L.) belongs to the Rosaceae family and is found in tropical and subtropical regions of Asia. The current investigation focused on the recovery of bioactive compounds from yellow nectarine peel using various green and other solvents, along with different drying techniques, such as freeze, vacuum, and hot-air oven, and energy-assisted extraction techniques, viz. ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and ultrasound-coupled microwave-assisted extraction (UMAE). The combined technique, viz. ChCl: lactic acid + freeze-drying + UMAE, produced the highest TPC and TFC, which were 2389.0 ± 35.8^{a} mg GAE/100 g dry weight (DW) and 896.0 ± 19.6^{a} mg QE/100 g DW, respectively, followed by other solvents. Antioxidant activities using FRAP values ranged from 8830.7 ± 218.7 to 11833.0 ± 195.6 µmol TE/100 g DW, whereas ABTS varied from 12412.0 ± 190.0^{f} to 15819.7 ± 183.7^{a} µmol TE/100 g DW, followed by DPPH. Experimental results revealed that UMAE with ChCl solvent yielded the highest antioxidant recovery across all drying treatments, followed by MAE, UAE, and conventional extraction techniques using NADES and other solvents, reaching EYs of 31.2%. Storage stability of peel extracts was evaluated at different temperatures, with low-temperature storage significantly improving total phenolics and antioxidant levels, whereas higher temperatures and light exposure accelerated degradation. This study offers a fresh perspective on maximizing the bioactive potential of yellow nectarine peel, bolstering its use as a functional food, nutraceutical, and cosmetic component.

Contribution/Originality: This study contributes to the existing literature by investigating an optimized green extraction strategy that maximizes the recovery of health-promoting compounds. It demonstrates that nectarine peel is a sustainable source of natural antioxidants and functional ingredients, supporting circular bioeconomy and waste valorization initiatives, together with a storage stability study.

1. INTRODUCTION

The nectarine (Prunus persica L.) is one of the most significant fruit crops, ranked second only to the apple in temperate zones worldwide, known for its organoleptic qualities, high antioxidant content, and nutritional value (Manganaris et al., 2022; Veerappan, Natarajan, Chung, & Park, 2021). Despite its potential health benefits, the Assamese variety "Hombogori" is underappreciated due to limited awareness of its edible and therapeutic properties. Enriching the applications of this nectarine variety could provide substantial health and ecological benefits.

Fresh and canned yellow-skinned nectarines, as well as processed foods, are very valuable and profitable types of nectarine (Prunus persica (L.)). With various skin colors, such as yellow, golden, and orange, nectarines contain different phytochemicals and bioactive compounds. Carotenoids give nectarine fruit its bright yellow, orange, and red colors and are now documented for their nutritional value (Zhao et al., 2022).

People use fruit as part of their lives, and as the need for dietary supplements has grown, people's insight into the health-promoting value of fruits has grown; so too have fruit cultivation systems. Due to increasing population size, fruit production is consistently escalating owing to rising demand brought on by metropolitan expansion, shifting dietary patterns, and environmental change.

Food waste refers to excluded, lost, spoiled, or pest-contaminated items. Companies can throw away valuable waste or repurpose it for functional dietary ingredients, tailoring their approaches to stay competitive in the commercial market (Boruah & Ray, 2024). Degradation may occur due to unfavourable handling and storage conditions for fruits, leading to significant food loss.

Various drying techniques are employed to reduce waste and prolong shelf life. Conventional drying approaches may adversely affect fruit quality by exposing it to high temperatures and oxygen. Vacuum drying preserves bioactive compounds due to mild processing temperatures, despite potentially longer processing times. Freeze-drying is an effective method for maintaining product quality by sublimating ice directly into vapour (Ferreira et al., 2020; Ge et al., 2024). For the extraction of beneficial compounds from nectarines using high-frequency sound waves and cavitation, ultrasound acts as a promising pretreatment method to enhance the extraction of beneficial compounds from nectarines (da Silva, Nunes, & Hoskin, 2023; Sim et al., 2024). This process offers benefits over traditional extraction techniques, including reduced energy and solvent use and shorter processing times, thereby enhancing ecological sustainability.

Valuable ingredients like antioxidant extracts and functional flours are produced by the valorization of fruit waste, enabling the resource-efficient management of fruit-derived residues. Efficient extraction methods utilizing "green" or "novel" technologies (Boruah & Ray, 2025) and natural deep eutectic solvents (NADESs) are under investigation, despite challenges related to viscosity and expense. Techniques such as ultrasound-assisted natural deep eutectic solvent extraction establish excellent recovery efficiency and methodological reliability (Hashemi, Shiri, Švec, & Nováková, 2022; Kaoui, Chebli, Zaidouni, Basaid, & Mir, 2023).

Due to their comparatively low toxicity and biodegradable nature, sugars, carboxylic acids, choline chloride (ChCl), amino acids, and other primary metabolites are now used in the food-related industry as extraction media for bioactive compounds from diverse food waste valorisation in several fields (Mero, Mezzetta, De Leo, Braca, & Guazzelli, 2024).

Mihaylova, Popova, Desseva, Manolov, et al. (2021) studied the characterization and comparison of three early- and two mid-ripening peach and nectarine varieties first, and propositions were then made about the most beneficial variety in terms of nutrient quality. Ferric Reducing Antioxidant Power (FRAP), Cupric Reducing Antioxidant Capacity (CUPRAC), 2,2-Diphenyl-1-picrylhydrazyl (DPPH), and 2,2-Azinobis (3-Ethylbenzothiazoline-6-Sulfonic Acid (ABTS) methods were determined for polyphenolic compounds and antioxidant activity with 80% aqueous methanol (methanol: water, 80:20, v/v) and ultrasonication.

The development of nutraceuticals involves bioactive compounds such as flavonoids and anthocyanins that have the potential to combat oxidative stress, inflammation, and chronic disease (Lara et al., 2020; Redondo, Venturini, Oria, & Arias, 2016). Petruccelli et al. (2023) studied the qualitative indices and chemical attributes of 32 peach cultivars and 52 nectarine cultivars with yellow and white flesh to translate the knowledge into practice of this extensively consumed fruit with influential functions for physiological health.

To incorporate fruit flours into different food formulations, extrusion cooking, combined with high temperatures and pressure, modifies the physicochemical properties of food ingredients by using different technologies to valorize them, improving protein denaturation, digestibility, phenolic extractability, starch

gelatinization, palatability, and bioactivity, while reducing antinutritional compounds (Culetu, Susman, Duta, & Belc, 2021). Moreover, extrusion is a scalable, low-waste process compatible with industrial production. To prepare an extruded gluten-free formulation, the incorporation of 15% peach peel flour enhanced antioxidant capacity, increased TDF content, and lowered the predicted glycemic index compared to the non-extruded byproducts (Martín-Diana et al., 2025a).

Lactic acid with glycerol as NADES solvent in a 1:1 ratio was used in homogenizer-assisted extraction. Chlorogenic acid and total polyphenols were used as dependent variables, and independent variables such as different water percentages (v/v), three extraction times, and three different homogenizer speeds were applied to peach peels (Şahin & Bilgin, 2022).

Strong antioxidant activity, flavonoids, polyphenols, tannins, sugars, pectin, anthocyanins, iridoids, ursolic acid, carotenoids, carbohydrates, and organic acids are all present in cornelian cherry (Cornus mas). Because cornelian cherry fruit extract has antioxidant qualities, it may be utilized successfully in the cosmetics business (Nizioł-Łukaszewska et al., 2018; Stoenescu, Trandafir, & Cosmulescu, 2022).

Redondo et al. (2021) reported that nectarine exhibited the highest total phenolic content, flavonoid content, and antioxidant activity among apricot, cherry, flat peach, peach, plum, and nectarine. The authors stated that bioavailability and a low degree of polymerisation have been reported for a major class of phenolics called proanthocyanidins present in flat peach, nectarine, and cherry.

Furthermore, previous inquiries have focused on conventional organic solvents and extraction strategies employing a single experimental approach, often neglecting the synergistic interactions of ecologically responsible natural deep eutectic solvents (NADES), technology-assisted drying methods, and energy-assisted extraction methods on the recovery of health-promoting compounds. As a result, few systematic comparative studies incorporate multiple drying techniques (freeze-drying, oven-drying, and vacuum-drying), green solvents, and extraction technologies such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and ultrasound–microwave-assisted extraction (UMAE).

Regarding *Prunus persica L.* peel, ultrasound-assisted microwave extraction from peach peel using NADESs has been proposed to date, while not much literature on nectarine peel and DESs has been documented so far. A significant gap in this research is the absence of a thorough estimation of the deterioration of peel-derived bioactive extracts, which is crucial for their commercial use as nutritionally enhanced additives. A systematic investigation incorporating a storage stability study with sustainable solvents, optimum drying techniques, and sophisticated extraction techniques is needed to enhance the recovery, preservation, and application of bioactive chemicals from nectarine peels. It has not been thoroughly researched how these processing techniques affect extraction yield, phenolic retention, flavonoid recovery, and antioxidant activity. This study combines the impact of green solvents with drying procedures and extraction methods on the storage conditions, recovery, and stability of bioactive chemicals from nectarine peel, filling in these gaps for further research.

2. MATERIALS AND METHODS

2.1. Chemicals

Sigma-Aldrich supplied the reagents for NADES solvents. Gallic acid, sodium acetate, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), 2,2-diphenyl-1-picrylhydrazyl (DPPH), quercetin, Folin-Ciocalteu reagent, and 2,2′-azino-bis [3-ethylbenzthiazoline sulfonate (ABTS), potassium chloride buffer (0.025 M, pH 1.0), sodium acetate buffer (0.4 M, pH 4.5), acidified ethanol, and distilled water were purchased from S.L. Fisher Scientific provided analytical-grade versions of the other reagents that were not specified.

2.2. Sample Collection and Preparation

During the rabi season, the collection and preparation of yellow nectarines occurred in Dhemaji district (latitudes 27°16'N and 27°52'N and longitudes 94°12'E and 95°26'E), Assam, India. This variety is classified as Prunus persica (L.) Batsch in the Rosaceae family, has a distinct coloration compared to other nectarines. The fruits were washed with distilled water, and the peel was removed with a knife, sealed in airtight polyethylene bags, and stored at -4 °C until future laboratory analysis.

2.3. Drying Pretreatments

The drying pretreatments included freeze-drying, vacuum drying, and hot-air drying, each implemented to reduce moisture content and estimate the methods' effectiveness in protecting bioactive components.

2.3.1. Freeze Drying

Nectarine peels were stored in 0.5 cm-thick containers at -20 °C for 48 hours, then freeze-dried for six hours at a vacuum of 3 mbar.

2.3.2. Vacuum Drying

Nectarine peels were sliced into 0.5 cm pieces, placed in glass containers, and dried in a vacuum dryer at 40 °C and 48 ± 3 mbar for five hours.

2.3.3. Hot Air Drying

Samples were placed on perforated trays in a laboratory oven dryer and dried for 12 hours at 60 ± 2 °C and 1.0 m/s air velocity until constant weight was achieved.

The dried peels from all three drying treatments were ground to approximately 0.35 mm particle size and then stored at -20 °C for further extraction.

2.4. Extraction

The present study systematically compares extraction techniques, such as UMAE, MAE, UAE, and a traditional extraction process, combined with three drying processes and four different solvents, which were lacking in previous studies that generally focused on a single extraction or drying process. Based on the target constituents to be recovered, the appropriate solvents were chosen. The natural deep eutectic solvent consists of choline chloride with glycerol, lactic acid, and acetic acid, diluted with water in a 7:3 v:v ratio; the conventional solvent is ethanol: water (8:2 v:v).

2.4.1. Preparation of NADES Solvent

With a few modifications, the heat-and-stirring process outlined by Rodríguez-Martínez et al. (2022) was used to produce the NADES. Using choline chloride as a hydrogen bond acceptor (HBA) and three carboxylic acid-based hydrogen bond donors (HBD) (lactic acid, acetic acid, and glycerol), three distinct NADESs were created with a 1:2 molar ratio and 30% water. Based on the raw materials, these NADES solvents were selected based on recent articles (Elgharbawy et al., 2019; Ramírez-Sucre, Avilés-Betanzos, López-Martínez, & Rodríguez-Buenfil, 2024; Tien, Le, Khoi, & Richel, 2022). Before being employed, the choline chloride used to make NADES was dried in a vacuum dryer at 40 °C for 24 hours at 220 V and 1000 W. The mixtures were heated and stirred at a speed of 350 rpm and a temperature of 70 °C for 2.5 h until a homogeneous and stable mixture with no visible precipitate was obtained.

2.4.2. Viscosity and pH Measurement

With a few adjustments, the viscosity analysis was carried out in accordance with Pires et al. (2025). A Brookfield digital viscometer running at 100 rpm was used to estimate the viscosity of prepared NADESs. An externally coupled hot-water bath was used to maintain the temperature. To find out how temperature adjustments changed the viscosity of NADESs with varying water contents, each NADES sample was tested at 40 °C.

A modified version of Sazali et al. (2023) was used to test the pH. With an inaccuracy of less than 1%, a pH meter measured pH in 5 °C increments at 40 °C.

2.4.3. Conventional Extraction of Phytochemicals

Prepared solvents were used at a fixed concentration (70%) in the traditional solvent extraction process reported by Neog et al. (2025), with minor modifications. 4 g of peel powder was mixed with 40 mL of selected solvents and placed in a thermostatically controlled water bath with continuous magnetic stirring at 50 ± 2°C for 60 min, then centrifuged to cool and extract bioactive chemicals from yellow-skinned nectarine peel.

2.4.4. Ultrasound-Assisted Extraction

Using Chanioti and Tzia (2018) with modifications, a probe-type ultrasound machine with 60% amplitude was used to sonicate 4 g of peel powder with prepared solvents at 20 kHz and a 5 s on/5 s off pulse mode for 20 minutes to extract bioactive chemicals from yellow-skinned nectarine peel with 40 mL of selected solvents. To minimize thermolabile compounds, the sample vessel was immersed in an ice-water bath during sonication to maintain the temperature below 50 ± 2°C.

2.4.5. Microwave-Assisted Extraction

Using Airouyuwa, Mostafa, Riaz, and Maqsood (2022) as a guide, with adjustments, 4 g of dried material was combined with 40 mL of prepared solvents and placed in a sealed, microwave-compatible extraction vessel at 300 W for 10 minutes while maintaining the extraction temperature at 50 ± 2°C for each investigational test.

2.4.6. Ultrasound-Assisted Microwave Extraction

For the UMAE extraction process, the technique of Sahlan et al. (2025) was adapted with modifications. A probe-type ultrasound machine with 60% amplitude was used to sonicate 4 g of peel powder with 40 mL of prepared solvents at 20 kHz in a 5 s on/5 s off pulse mode for 20 minutes, followed by microwave irradiation at 300 W for 10 minutes, while maintaining the extraction temperature at 50 ± 2°C.

2.4.7. Extraction Yield

All solvent-extracted supernatants were dried in a rotary vacuum evaporator, and the optimal extraction solvent was preferred based on key factors, such as extraction yield and health effects. The EYs were calculated as follows using Equation 1.

$$EY\% = \frac{The\ mass\ of\ the\ extract\ after\ solvent\ removal}{Initial\ mass\ of\ the\ sample} \times 100 \qquad (1)$$

3. PHYTOCHEMICAL SCREENING

Utilizing numerous qualitative inspections, the presence of various phytochemical compounds in extracts was proven. Wagner's test detects alkaloids through a brownish-red precipitate after mixing 2 mL of peel extract with Wagner's reagent (Singh & Kumar, 2017). The formation of foam indicates saponins, as explained by shaking a blend of 5–10 mL of extract and sodium carbonate strongly for fifteen minutes (Kancherla, Dhakshinamoothi, Chitra, & Komaram, 2019). To test for cardiac glycosides, 4 mL of evaporated extract was incorporated with

methanol, alcoholic KOH, and 3–4 drops of 1% alcoholic 3,5-dinitrobenzene, followed by heating; a loss of violet color indicates their presence (Jagessar, 2017). The Lieberman-Burchard test reveals steroids if a green color appears when 2 mL of acetic anhydride and 1 mL of extract are mixed with concentrated sulfuric acid (Pooja & Vidyasagar, 2016).

Mixing isopropyl alcohol and concentrated ammonium hydroxide with 10 mg of dried extract gives a red color hue for anthraquinones after two minutes (María et al., 2018). 2 mL of 2 M HCl and ammonia mixed with 2 mL of sample extract gives a blue-violet hue for the anthocyanin test (Gupta, Kumari, & Tiwari, 2020). For coumarins, a yellow hue is obtained when 2 mL of extract is combined with 3 mL of 10% NaOH. A greenish-black color is obtained for phenols with a mixture of 1 mL of 5% ferric chloride solution and 5 mL of extract (Godlewska, Pacyga, Najda, & Michalak, 2023). 1 mL of the extract with distilled water and a ferric chloride mixture gives a blue-green color for tannins in Braymer's test (Singh & Kumar, 2017).

The magnesium hydrochloride reduction test is used for flavonoids, as indicated by a pink-tomato-red color resulting from the involvement of powdered magnesium and hydrochloric acid in the extract (Pooja & Vidyasagar, 2016). A dried sample extract mixed with antimony trichloride gives a carotenoid test by a blue-green color that changes to red (Jagessar, 2017). Mixing the extract with copper sulfate, ethanol, and KOH pellets; the occurrence of a pink solution gives confirmation of the presence of amino acids by the Biuret test (De Silva, Abeysundara, & Aponso, 2017). Benedict's test indicates reducing sugars through a yellowish-red color developed after boiling the blend of extract and Benedict's reagent (Singh & Kumar, 2017).

4. PHYTOCHEMICAL CONTENT AND ANTIOXIDANT ACTIVITY

The total phenolic content and total flavonoid content were employed to identify bioactive substances.

The techniques of Mokrani and Madani (2016) and Plazzotta, Ibarz, Manzocco, and Martín-Belloso (2021) were used to determine the quantity of TPC and TFC in peel extracts. For TPC, 100 µL of diluted extract was mixed with 500 µL of 10% (v/v) Folin-Ciocalteu reagent. After 5 mins of resting, 400 µL of 7.5% (w/v) sodium carbonate was added, mixed thoroughly, and incubated for 30 mins at room temperature. The absorbance was measured at 765 nm using a UV–Visible spectrophotometer.

For TFC, 500 µL of diluted extract was mixed with 150 µL of 5% (w/v) sodium nitrite ($NaNO_2$) solution. After a 5-minute resting period, 1.0 mL of 1 M sodium hydroxide (NaOH) was added, and the volume was adjusted to 5 mL. The absorbance was recorded at 510 nm using a UV–Visible spectrophotometer.

The results were expressed for TFC in mg QE/100 g DW and for TPC in mg GAE/100 g DW.

5. TOTAL ANTIOXIDANT CAPACITY (TAC)

The ferric reducing antioxidant power assay (FRAP) and two free-radical assays, 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonate) (ABTS+) and 2,2-diphenyl-1-picrylhydrazyl (DPPH), were used to evaluate the extracts' total antioxidant capacity (TAC).

5.1. The modification of Mansinhos et al. (2021) was used to assess the DPPH radical test. 300 µL of diluted extract was added to 3 mL of freshly prepared 90 µM DPPH solution in methanol. The mixture was vortexed and incubated for 30 min in a dark room. The decrease in absorbance was recorded at 517 nm using a UV–visible spectrophotometer.

5.2. A modified version of the Saikia and Mahanta (2016) method was used for the FRAP test. 100 µL of diluted extract was added to 3 mL of FRAP reagent, vortexed, and incubated at 30°C for 10 min. The increase in absorbance was measured due to the formation of the Fe^{2+}–TPTZ complex at 593 nm using a UV-visible spectrophotometer.

5.3. According to Martín-Diana et al. (2025b), a modified version of the method was used to conduct the ABTS test. 100 µL of diluted extract was mixed with 3.9 mL of ABTS working solution (mixing 7 mM ABTS stock

solution with 2.45 mM potassium persulfate ($K_2S_2O_8$)); the mixture was vortexed and incubated for 6 min in a dark room. The absorbance was recorded at 734 nm in a UV-visible spectrophotometer.

The results of all three tests were represented as µmol TE/100g DW, with Trolox (0.025–0.3 mM) serving as the standard.

6. QUENCHER ASSAYS

Additionally, the TPC technique was used on non-extracted solid samples (Q-TPC) to assess the bioactive components of the materials. The total antioxidant activity of the materials was also evaluated by applying FRAP, ABTS+, and DPPH methods to non-extracted solid samples (Q-DPPH, Q-FRAP, and Q-ABTS•+).

6.1.Q-TPC Assay

The FC assay model created by Del Pino-García, García-Lomillo, Rivero-Pérez, González-SanJosé, and Muñiz (2015) served as the basis for this method's adaptation. 10 mg of the weighed product was mixed with 6 mL of distilled water and vortexed for 30 seconds. Add 0.5 mL of diluted FC reagent and mix thoroughly. After a resting period of 5 minutes at room temperature, add 1.5 mL of 7.5% (w/v) sodium carbonate solution. Adjust the volume up to 10 mL, and after 1.5 h of orbital shaking, the absorbance was recorded at 765 nm with a UV-visible spectrophotometer. The FC index was estimated as mg GAE/100 g DW.

6.2.Q-DPPH Assay

Martín-Diana et al. (2025a) was the source of this adaptation. Mix 10 mg of the dried powdered sample with 10 mL of 0.10 mM DPPH solution, vortex for 30 seconds, and incubate for 60 minutes with orbital shaking in a dark room. Record the absorbance at 517 nm against a methanol blank. The Q-DPPH index was estimated as µmol TE/100 g DW.

6.3.Q-ABTS•+ Assay

Martín-Diana et al. (2025a) is the source of the Q-ABTS•+ technique. Add 10 mg of dried powder to 10 mL of freshly prepared ABTS•+ reagent, vortex for 30 seconds, and incubate in a dark room for 30 minutes with orbital shaking. Record the absorbance at 734 nm using a UV-Visible spectrophotometer. The Q-FRAP index was estimated as µmol TE/100 g DW.

6.4.Q-FRAP Assay

The Del Pino-García et al. (2015) technique served as the model for the Q-FRAP methodology, with a few minor modifications. Add 10 mg of dried powder to 10 mL of freshly prepared FRAP reagent, vortex for 30 seconds, and incubate at 30 °C for 20 mins with orbital shaking. Record the absorbance at 593 nm using a UV-Visible spectrophotometer. The Q-FRAP index was expressed as µmol TE/100 g DW.

7. STORAGE STABILITY OF PEEL EXTRACTS

The peel extracts prepared using the best procedure were subjected to various conditions to support the use of this extractant as a sustainable medium. The samples were kept at room temperature (25 °C) in the dark and in light, in a refrigerator (4 °C), and in a freezer (-20 °C) to assess the products' storage durability. Furthermore, the impact of sunshine on oxidation was assessed. The initial concentrations of TPC, TFC, DPPH, FRAP, and ABTS were all the same in the extract samples. Total phenolic content, total flavonoid content, FRAP, ABTS, and DPPH were all measured regularly. It took sixty days to complete this storage stability test.

8. STATISTICAL ANALYSIS

For statistical analysis, Origin and Microsoft Excel were utilized. To identify differences in mean values, Tukey's post hoc tests and analysis of variance were used. At least three experiments were conducted, and the data were presented as the mean ± standard deviation. A p-value of less than 0.05 was utilized to determine significance.

9. RESULTS AND DISCUSSION

9.1. Viscosity and pH of NADES Solvent

Due to increased kinetic energy and reduced intermolecular interactions, natural deep eutectic solvents (NADESs) exhibit decreasing viscosity as temperature rises. NADESs prepared with acetic acid, an organic acid, show considerably higher acidity than ChCl: Glycerol. The pH of ChCl: Glycerol is below 7 because glycerol contains acidic hydrogen atoms. Viscosity, a critical fluid property that reflects internal resistance to flow, is strongly influenced by the state of hydrogen-bond donors (HBDs) at room temperature. At 40°C, the viscosities of various DESs are noted: ChCl: LA at 18 mPa s (pH 2.2), ChCl: Gly at 10 mPa s (pH 4.5), and ChCl: AA at 7 mPa s (pH 2.4). In Airouyuwa et al. (2022), increasing molar volume and enhancing molecular mobility between HBDs and hydrogen-bond acceptors (HBAs) were observed, and viscosity decreased with temperature over the range from 40 to 60°C. Increasing the LA/Gly molar ratio increases viscosity; the viscosities of ChCl: Gly (0.235–0.453 Pa s) and ChCl: LA (0.04–0.06 Pa s) also decrease with temperature (Sazali et al., 2023).

According to Fanali et al. (2021), the ChCl–lactic acid (1:2) solvent exhibits shear-thinning behavior across all tested temperatures, with viscosity decreasing as shear speed increases. This is attributed to the splintering of the solvent's internal structure and thermal expansion. Viscosity is inversely related to water content, with measurements showing 18.33 mPas for 0% water, 7.77 mPas for 15%, and 3.01 mPas for 35% added water at 80 °C. Increasing water content increases the mixing of the extraction solvent, and the percentage decrease in viscosity with temperature (from 20 °C to 80 °C) was approximately 90% for all water percentages tested. Table 1 contains details on viscosities, pH, and NADES compositions.

Table 1. NADES abbreviations, constituents, pH, and viscosity (mPa s.) at 40 °C.

Solvent abbreviation	NADES Composition	Formulation	Viscosity (mPa s) at 40 °C	pH at 40 °C
ChCl: AA	Choline Chloride: Acetic acid: Water	1:2 + 30% water	7	2.4
ChCl: Gly	Choline Chloride: Glycerol: water	1:2 + 30% water	10	4.5
ChCl: LA	Choline Chloride: Lactic acid: water	1:2 + 30% water	18	2.2

Fluid transfer has an elevated energy demand for the challenges faced by chemical processing, as the temperatures exceed 115°C; the viscosity of ChCl: LA approaches that of water (0.01 Pa s) (Abbasi et al., 2023; Ameen et al., 2023; Bokhari, Yusup, Asif, Chuah, & Michelle, 2020; Cao et al., 2023). The highest pH values (4.1–4.5) of a 1:2 M ratio of ChCl: Gly solvent with temperature variability (25–60 °C) were found in the study by Skulcova, Russ, Jablonsky, and Sima (2018) among all the ChCl-based DES used in the study, due to the presence of alcohol groups in the DES structure. The pH of ChCl: LA ranges from 0.99 to 1.8 for the molar ratios of 1:5 and 1:10 under similar circumstances

9.2. Phytochemical Screening of Nectarine Peel

Unlocking several opportunities for sustainable alternatives, this study suggests the potential for these phytochemicals to be utilized in the food sector. To qualitatively analyze metabolites, standard methods were employed for aqueous and ethanolic extracts of *Prunus persica* L. leaves, revealing tannins, saponins, phlobatanins, and flavonoids present in both types of extracts, after the analysis of whole tannins, saponins, phlobatanins, flavonoids, terpenoids, cardiac glycosides, and alkaloids (Edrah, Alafid, & Kumar, 2015).

Along with nectarine peel extracts, ten distinct types of phytochemicals have been tested in several studies. No existing research on the analysis of Prunus persica L. peel for tannins and saponins was identified, as in pequi (Caryocar brasilense Camb.) peel flours (Cangussu, Leão, Oliveira, & Franca, 2021). To promote sustainability, the ability to recover bioactive components from peels represents an economical and eco-friendly strategy for waste. The significance of various phytochemicals and antioxidants in the peel was emphasised in this current research. To potentially nullify the advantages of waste diversion, certain waste valorization techniques may incur high environmental costs through chemical treatments and energy-intensive processes. Hence, the environmental impacts must be meticulously assessed to ensure sustainability. The symbols (-), (+), (++), and (+++) denote the presence of phytochemicals: (-) = absence, (+) = traces, (++) = moderate, and (+++) = abundance of phytochemicals in the phytochemical studies in Figures 1(a, b, c, d).

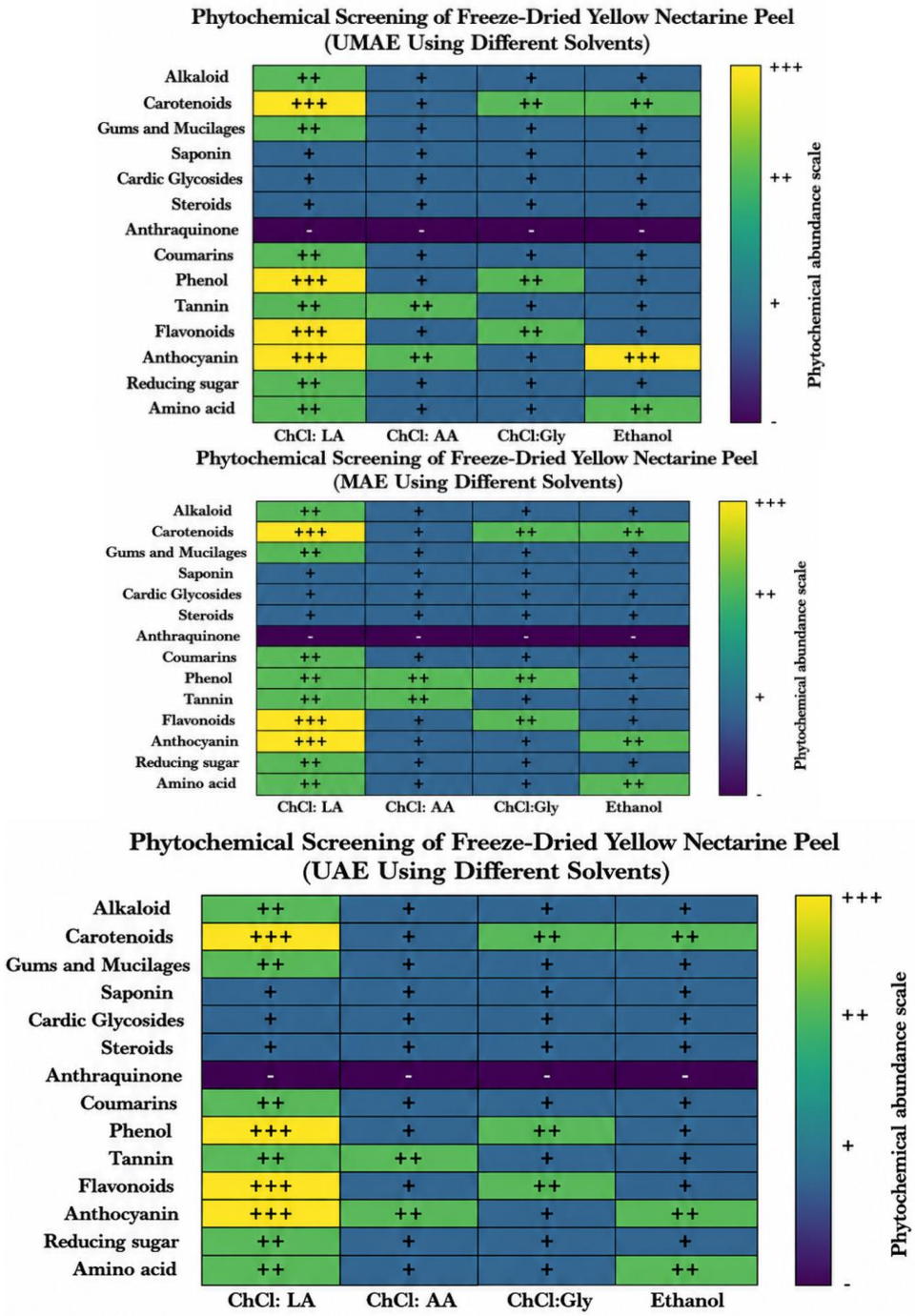

Figure 1(a). Phytochemical Screening of Freeze-Dried Nectarine Peel Extract Using UMAE, MAE, and UAE along with Different Solvents.

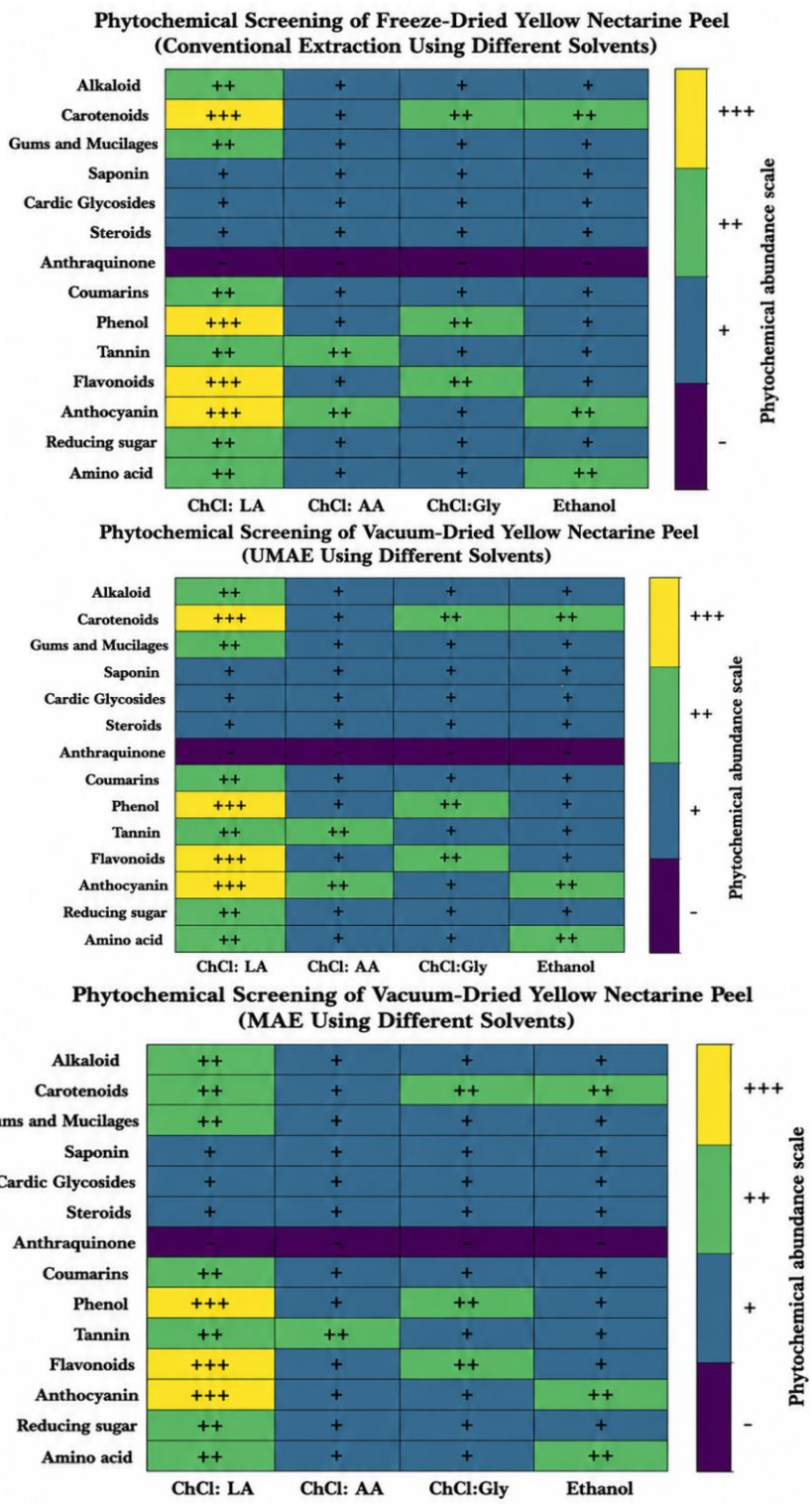

Figure 1(b). Phytochemical Screening of Freeze-Dried and Vacuum-Dried Nectarine Peel Extract Using Conventional Extraction, UMAE, and MAE along with Different Solvents.

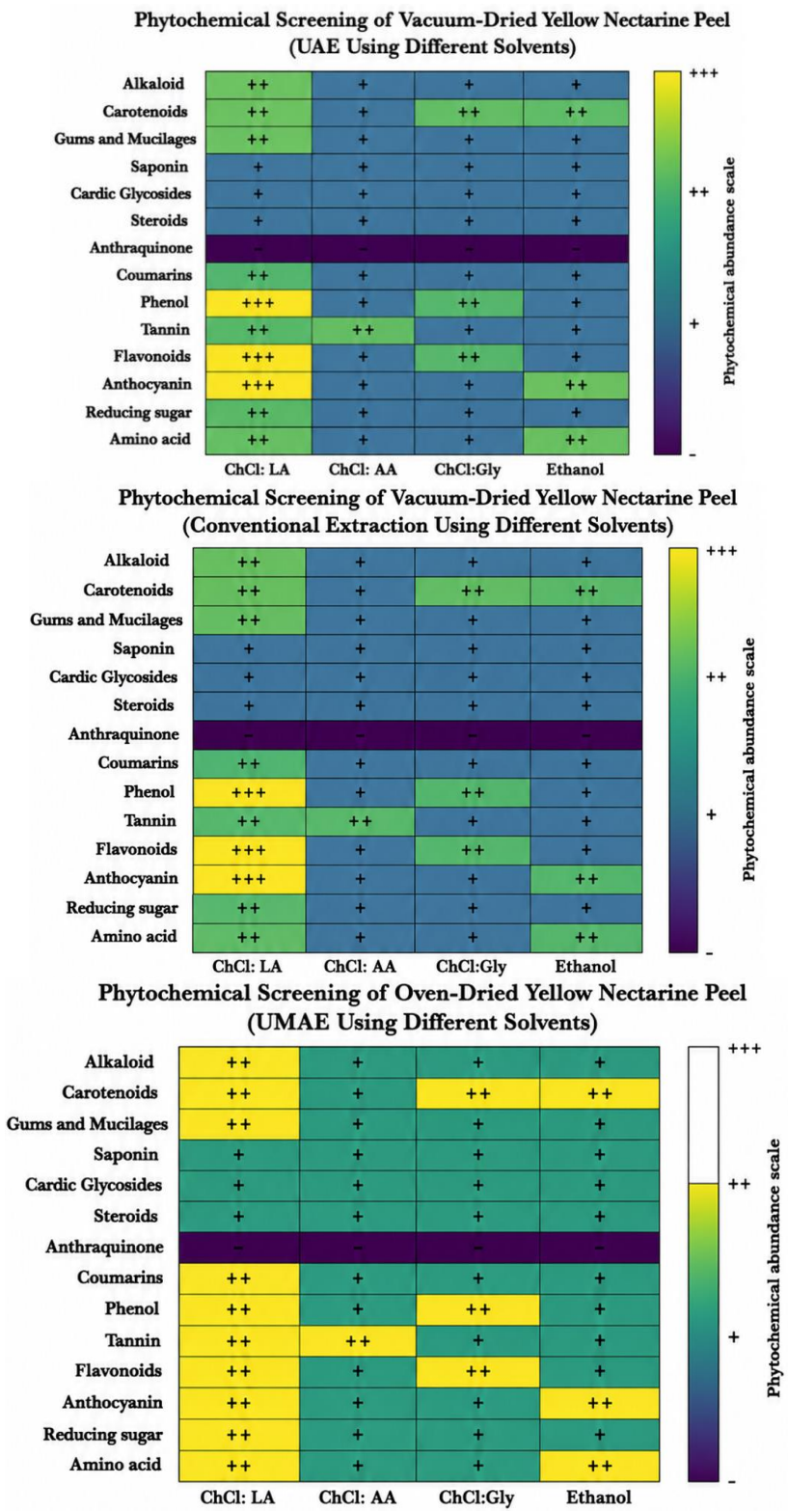

Figure 1(c). Phytochemical Screening of Vacuum Dried and Oven Dried Nectarine Peel Extract Using UAE, Conventional Extraction and UMAE along with Different Solvents.

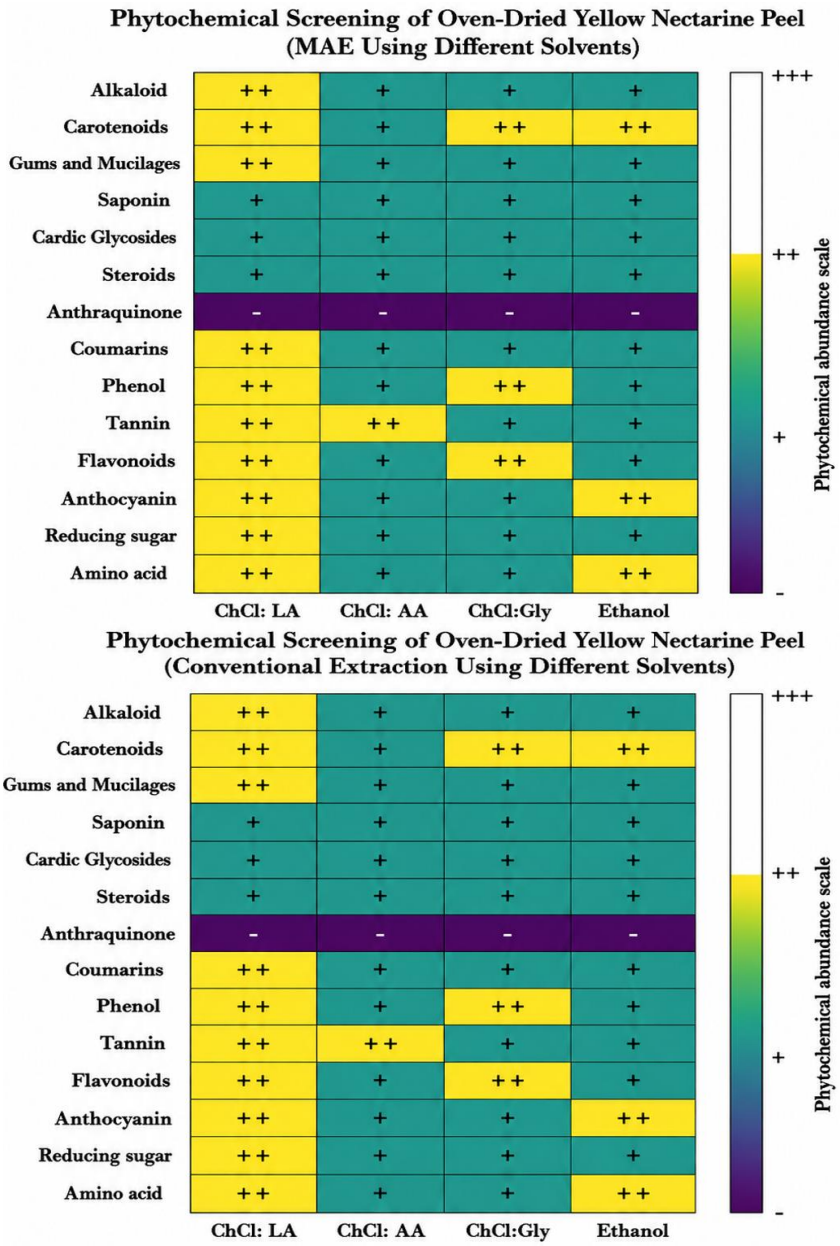

Figure 1(d). Phytochemical Screening of Oven-Dried Nectarine Peel Extract Using MAE and Conventional Extraction along with Different Solvents.

The seeds of Prunus persica L. have cyanogenic and phenolic glycosides investigated for their anti-allergic inflammatory effects by Kim et al. (2013), while Backheet, Farag, Ahmed, and Sayed (2003) analysed the leaves and stem bark of Prunus persica (L.) Batsch and identified flavonoids and cyanogenic glycosides.

Various extraction techniques are employed to recover phytochemicals from yellow nectarine peel. The highest phytochemical abundance, with enhanced solvent penetration and mass transfer, occurred with ultrasound-microwave-assisted extraction (UMAE), outperforming ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), while lower phytochemical intensity occurred with the conventional method. Due to thermal damage, oven drying was performed as a low-key method, while the most phytochemicals were recovered by freeze-drying, particularly sensitive compounds. The optimal approach combines freeze-drying with UMAE to maximize phytochemical content and maintain bioactive components.

10. EXTRACTION OF BIOACTIVE CONSTITUENTS FROM YELLOW-FLESHED NECTARINE PEEL

Using different extraction procedures (UMAE, MAE, UAE, and conventional extraction) and different drying methods with various solvents (ChCl: LA, ChCl: Gly, ChCl: AA, and ethanol), the yellow nectarine peel extracts had TPC and TFC. The impact of phenolic recovery by the solvent system and processing conditions was shown in the results, according to statistical analysis, which showed significant differences across treatments ($p < 0.05$).

10.1. Total Phenolic Content

In this study, in combination with freeze-drying and ultrasonic–microwave-assisted extraction (UMAE), the highest phenolic yield of 2389.0 ± 35.8^{a} mg GAE/100 g DW using a ChCl: LA solvent, where the other effective combinations included ChCl: Gly + FD + UMAE (2306.7 ± 42.1^{a} mg GAE/100 g DW) and ChCl: AA + FD + UMAE (2278.0 ± 22.9^{a} mg GAE/100 g DW). Due to strong hydrogen-bonding interactions that enhance phenolic solubilization, the recovery of an ethanol-based system yielded 2229.0 ± 13.1^{a} mg GAE/100 g DW, lower than that of DES-based solvents. Table 2 states the different extraction conditions for total phenolic content in nectarine peel. Mihaylova, Popova, Desseva, Dincheva, and Tumbarski (2023) reported total phenolics of peach peels at 50 °C for 30 minutes with 80% EtOH as 6.82–13.12 mg GAE/g dw using UAE, alongside notable anthocyanins and flavonoids from various Bulgarian cultivars.

Table 2. Total phenolic content for different extraction conditions for nectarine peel.

Extraction Conditions	TPC	Extraction Conditions	TPC	Extraction Conditions	TPC	Extraction Conditions	TPC
ChCl:LA + FD + UMAE	2389.0 ± 35.8^{a}	ChCl:Gly + FD + UMAE	2306.7 ± 42.1^{a}	ChCl:AA + FD + UMAE	2278.0 ± 22.9^{a}	Ethanol + FD + UMAE	2229.0 ± 13.1^{a}
ChCl:LA + FD + MAE	2119.7 ± 33.8^{b}	ChCl:Gly + VD + UMAE	2006.7 ± 20.8^{b}	ChCl:AA + VD + UMAE	1946.3 ± 28.3^{b}	Ethanol + TD + UMAE	1902.7 ± 16.3^{b}
ChCl:LA + VD + UMAE	2063.0 ± 25.1^{c}	ChCl:Gly + FD + MAE	1990.7 ± 34.1^{bc}	ChCl:AA + OD + UMAE	1920.3 ± 15.5^{bc}	Ethanol + OD + UMAE	1884.0 ± 16.9^{c}
ChCl:LA + OD + UMAE	2022.7 ± 18.0^{cd}	ChCl:Gly + OD + UMAE	1973.3 ± 20.8^{c}	ChCl:AA + FD + MAE	1884.0 ± 23.1^{c}	Ethanol + FD + MAE	1845.3 ± 15.5^{d}
ChCl:LA + VD + MAE	1915.3 ± 19.6^{d}	ChCl:Gly + VD + MAE	1869.3 ± 18.0^{d}	ChCl:AA + VD + MAE	1826.0 ± 12.8^{d}	Ethanol + TD + MAE	1797.3 ± 14.6^{e}
ChCl:LA + FD + UAE	1884.0 ± 15.4^{de}	ChCl:Gly + FD + UAE	1815.0 ± 26.2^{e}	ChCl:AA + FD + UAE	1756.3 ± 17.2^{e}	Ethanol + TD + UAE	1679.0 ± 12.7^{f}
ChCl:LA + VD + UAE	1809.7 ± 19.1^{ef}	ChCl:Gly + VD + UAE	1767.0 ± 19.1^{f}	ChCl:AA + VD + UAE	1719.7 ± 15.4^{f}	Ethanol + FD + UAE	1676.7 ± 23.9^{g}
ChCl:LA + OD + UAE	1790.7 ± 23.2^{ef}	ChCl:Gly + OD + UAE	1731.3 ± 23.2^{fg}	ChCl:AA + OD + UAE	1669.7 ± 24.8^{g}	Ethanol + OD + MAE	1611.0 ± 24.4^{h}
ChCl:LA + OD + MAE	1760.7 ± 23.7^{fg}	ChCl:Gly + OD + MAE	1709.0 ± 19.7^{g}	ChCl:AA + OD + MAE	1651.0 ± 20.5^{gh}	Ethanol + OD + UAE	1610.7 ± 21.0^{i}
ChCl:LA + FD + Conve	1735.3 ± 31.5^{g}	ChCl:Gly + FD + Conve	1664.0 ± 17.7^{h}	ChCl:AA + FD + Conve	1617.7 ± 25.3^{h}	Ethanol + FD + Conve	1581.3 ± 22.3^{j}
ChCl:LA + VD + Conve	1685.3 ± 13.2^{h}	ChCl:Gly + VD + Conve	1651.0 ± 14.0^{h}	ChCl:AA + OD + Conve	1616.7 ± 19.9^{h}	Ethanol + TD + Conve	1576.3 ± 13.6^{k}
ChCl:LA + OD + Conve	1658.0 ± 16.5^{h}	ChCl:Gly + OD + Conve	1616.7 ± 19.9^{i}	ChCl:AA + VD + Conve	1610.7 ± 14.8^{h}	Ethanol + OD + Conve	1529.7 ± 16.2^{l}

Note: Values in the same column followed by different superscripts a,b,c,d,e,f,g,h,i,j were significantly different at $p < 0.05$. Data were expressed as mean ± SD (n=3).
a,b,c,d,f,g,h are different superscripts and have been inserted in the note of the table.

With vacuum-dried samples yielding the highest TPC values (2063.0 ± 25.1^{c} mg GAE/100 g DW for ChCl: LA), freeze-drying consistently produced higher total phenolic content (TPC) values than vacuum or oven drying among drying techniques. Due to its low-temperature and pressure conditions, freeze-drying preserved the heat-sensitive bioactive compounds much better than oven drying, which led to reduced TPC values. The extracts from "Morsiani 90" and "Evmolpiya" peels exhibited the highest TPC values at 115.71 and 107.01 mg GAE/100 g fw, respectively, contrary to other extracts below 65 mg GAE/100 g fw. These results are consistent with Liu, Cao, and Jiang (2015) but differ from those of Mokrani and Madani (2016).

In Zannou and Koca (2022), outperforming traditional solvents under certain conditions, the naturally derived deep eutectic solvents (NADESs) showed a total phenolic content ranging from 1.20 to 9.35 mg GAE/g. The improved viscosity due to their enhanced extraction efficiency is attributed to the optimal addition of 20% distilled water. However, due to high viscosity hindering mass transfer, some NADESs had lower extractability. In this current study, phenolic recovery varies with extraction methods, with TPC decreasing from 2389.0 mg GAE/100 g DW with UMAE to 1735.3 mg GAE/100 g DW with traditional extraction. Similar patterns were noted with different peach types, with cv. Golden exhibiting the highest phenolic levels and Shahpasand the lowest (Manzoor, Anwar, Mahmood, Rashid, & Ashraf, 2012). The study demonstrates that the phenolic recovery from yellow nectarine peel, pairing deep eutectic solvents with advanced extraction methods, is significantly enhanced.

10.2. Total Flavonoid Content

The study reveals significant variations in total flavonoid content (TFC) of nectarine peel extracts influenced by solvents, drying methods, and extraction techniques. Ultrasonic-Microwave Assisted Extraction (UMAE) with freeze-drying yielded the highest TFC of 896.0 ± 19.7^{a} mg QE/100g DW, attributed to enhanced solvent penetration, with freeze-drying outperforming other drying methods in flavonoid retention. In contrast, conventional methods produced the lowest outputs. Additionally, flavonoid glycosides were found in water extracts, showing 17.59 mg QE/100g fw, compared to 12.11 mg QE/100g fw from methanolic extracts. TFC varied by fruit variety, with values ranging from 17.76 ± 0.62 to 130.17 ± 0.81 mg RE/100g fw for pulp and 91.66 ± 1.05 to 299.86 ± 0.76 mg RE/100g fw for peel (Ferreira & Pinho, 2012). Historical comparisons indicate that peach peel TFC ranges from 599.7 to 785.5 mg CE/100g DW (Manzoor et al., 2012).

Table 3. Total flavonoid content for peel at different extraction conditions.

Extraction Conditions	TFC	Extraction Conditions	TFC	Extraction Conditions	TFC	Extraction Conditions	TFC
ChCl:LA + FD + UMAE	896.0 ± 19.7^{a}	ChCl:Gly + FD + UMAE	857.3 ± 15.8^{a}	ChCl:AA + FD + UMAE	840.0 ± 15.5^{a}	Ethanol + FD + UMAE	806.3 ± 17.4^{a}
ChCl:LA + FD + MAE	771.0 ± 23.4^{b}	ChCl:Gly + FD + MAE	711.0 ± 17.7^{b}	ChCl:AA + FD + MAE	663.7 ± 16.2^{b}	Ethanol + FD + MAE	643.7 ± 20.8^{b}
ChCl:LA + VD + UMAE	741.0 ± 17.0^{c}	ChCl:Gly + VD + UMAE	702.3 ± 15.6^{b}	ChCl:AA + TD + UMAE	646.7 ± 20.8^{b}	Ethanol + TD + UMAE	603.0 ± 15.8^{c}
ChCl:LA + FD + UAE	701.0 ± 17.0^{d}	ChCl:Gly + FD + UAE	662.7 ± 11.7^{c}	ChCl:AA + FD + UAE	632.0 ± 13.0^{c}	Ethanol + FD + UAE	595.3 ± 8.1^{c}
ChCl:LA + OD + UMAE	696.3 ± 15.3^{d}	ChCl:Gly + OD + UMAE	653.3 ± 17.0^{c}	ChCl:AA + OD + UMAE	603.3 ± 20.8^{d}	Ethanol + VD + MAE	572.0 ± 21.9^{d}
ChCl:LA + VD + MAE	671.0 ± 23.7^{e}	ChCl:Gly + VD + MAE	631.0 ± 13.0^{d}	ChCl:AA + VD + MAE	583.7 ± 18.8^{e}	Ethanol + OD + UMAE	546.7 ± 17.6^{e}
ChCl:LA + OD + MAE	643.3 ± 16.7^{f}	ChCl:Gly + OD + MAE	603.0 ± 14.5^{e}	ChCl:AA + OD + MAE	565.3 ± 13.4^{e}	Ethanol + OD + MAE	526.7 ± 14.7^{f}
ChCl:LA + VD + UAE	621.7 ± 19.4^{g}	ChCl:Gly + VD + UAE	585.0 ± 13.6^{f}	ChCl:AA + VD + UAE	541.3 ± 14.6^{f}	Ethanol + VD + UAE	512.3 ± 12.3^{f}

Extraction Conditions	TFC	Extraction Conditions	TFC	Extraction Conditions	TFC	Extraction Conditions	TFC
ChCl:LA + OD + UAE	601.0 ± 17.8^{h}	ChCl:Gly + OD + UAE	557.3 ± 16.0^{g}	ChCl:AA + OD + UAE	522.7 ± 12.5^{f}	Ethanol + OD + UAE	488.7 ± 13.7^{g}
ChCl:LA + FD + Conve	582.7 ± 15.0^{i}	ChCl:Gly + FD + Conve	544.7 ± 17.8^{g}	ChCl:AA + FD + Conve	518.0 ± 13.1^{f}	Ethanol + FD + Conve	486.7 ± 15.3^{g}
ChCl:LA + VD + Conve	518.7 ± 18.9^{j}	ChCl:Gly + VD + Conve	480.0 ± 13.5^{h}	ChCl:AA + VD + Conve	444.3 ± 15.1^{g}	Ethanol + VD + Conve	410.3 ± 12.7^{h}
ChCl:LA + OD + Conve	505.7 ± 13.7^{j}	ChCl:Gly + OD + Conve	474.3 ± 16.4^{h}	ChCl:AA + OD + Conve	441.7 ± 13.7^{g}	Ethanol + OD + Conve	407.0 ± 13.7^{h}

Note: Results were expressed as mean ± standard error of the mean (SEM). P values at < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, f, g, h, denote significant differences from each other at $p < 0.05$.

The efficiency of NADES solvents for flavonoid extraction compared with traditional organic solvents was studied in this investigation. The highest flavonoid concentrations were obtained (896.0 ± 19.7^{a} mg QE/100g DW) with the combination of ChCl: LA, surpassing those of other NADES and ethanol (806.3 ± 17.4^{a} mg QE/100g DW) due to the strong hydrogen bonding and adjustable polarity of NADES, which enhance extraction efficacy. Ultrasound- and microwave-assisted extraction with freeze-drying and NADES solvent was an optimal extraction method for maximizing flavonoid recovery from fruit peel, while traditional methods yielded significantly lower levels (407.0 ± 13.7^{h} mg QE/100g DW). Table 3 demonstrates the Total flavonoid content for the peel at different extraction conditions.

60% acetone achieved 363 mg GAE/100g total phenolic content (TPC) from peaches, over double the effectiveness of water (182 mg GAE/100g) and 60% ethanol (178 mg GAE/100g). For total flavonoid content (TFC), 60% ethanol was most efficient at 57 mg QE/100g, followed by 60% methanol and 60% acetone (Mokrani & Madani, 2016). The findings emphasize the necessity of optimizing extraction methods to recover bioactive compounds from peach byproducts.

Furthermore, the ST cultivar showed the highest levels, while HP and YP had the lowest. Total flavonoid concentrations and total phenolic contents in various peach cultivars ranged from 29.05 to 49.37 mg RE/100g and 33.51 to 62.77 mg GAE/100g, respectively. Due to their high antioxidant levels, peaches may have significant dietary implications (Wu et al., 2022). The research indicates that, for flavonoid extraction, amine-alcohol-based DESs, such as ChCl: LA, are more effective than sugar-carboxylic acid-based solvents due to their better solubilization properties (Shang et al., 2019). In this study, it is shown that freeze-drying paired with NADES solvents and ultrasound–microwave-assisted extraction optimally recovers phenolics and flavonoids while minimizing thermal damage to sensitive compounds from high-temperature methods.

11. DETERMINATION OF ANTIOXIDANT CAPACITY (TAC) OF YELLOW-FLESHED NECTARINE PEEL

With different drying methods and extraction procedures, the antioxidant reduction capacity of yellow nectarine peel extracts made with different solvents (ChCl: LA, ChCl: Gly, ChCl: AA, and ethanol) was assessed using the DPPH, ABTS, and FRAP assays.

11.1. ABTS Assay

The ABTS radical scavenging activity of peel extracts was determined in a study that explored the effects of extraction procedures, drying methods, and solvent systems, demonstrating significant effects ($p < 0.001$). The role of solvent selection and preprocessing in recovering antioxidant compounds emphasizes that antioxidant capacities were measured from 12412.0 ± 190.0^{f} to 15819.7 ± 183.7^{a}μmol TE/100 g DW. The combination of ChCl: LA deep eutectic solvent with freeze-drying and ultrasound–microwave-assisted extraction (FD + UMAE), the most effective method, resulted in the highest antioxidant activity of 15819.7 ± 183.7^{a}μmol TE/100 g DW. Table 4

shows the ABTS assay for peel under different extraction conditions. This combination outperformed other solvents, such as ChCl: Gly + FD + UMAE (15291.0 ± 191.7^{a}) and ChCl: AA + FD + UMAE (14605.0 ± 176.5^{a}), with a decline in antioxidant activity from FD + UMAE to VD + UMAE (15426.3 ± 207.9^{ab}) and OD + UMAE (15156.3 ± 181.2^{bc}). Table 4 shows the ABTS content for peel under different extraction conditions. The sublimation-based dehydration of the freeze-drying method can effectively maintain cellular integrity and prevent the thermal degradation of phenolic compounds, enhancing antioxidant activity in the freeze-dried samples.

Table 4. ABTS assay of yellow nectarine peel at different extraction conditions.

Extraction Conditions	ABTS	Extraction Conditions	ABTS	Extraction Conditions	ABTS	Extraction Conditions	ABTS
ChCl:LA + FD + UMAE	15819.7 ± 183.7^{a}	ChCl:Gly + FD + UMAE	15291.0 ± 191.7^{a}	ChCl:AA + FD + UMAE	14605.0 ± 176.5^{a}	Ethanol + FD + UMAE	14120.0 ± 182.1^{a}
ChCl:LA + VD + UMAE	15426.3 ± 207.9^{ab}	ChCl:Gly + VD + UMAE	14949.0 ± 209.6^{ab}	ChCl:AA + VD + UMAE	14571.7 ± 162.1^{a}	Ethanol + VD + UMAE	14030.0 ± 194.0^{a}
ChCl:LA + FD + MAE	15409.7 ± 243.2^{ab}	ChCl:Gly + FD + MAE	14924.3 ± 244.2^{ab}	ChCl:AA + OD + UMAE	14335.0 ± 179.2^{ab}	Ethanol + OD + UMAE	13843.3 ± 160.2^{ab}
ChCl:LA + OD + UMAE	15156.3 ± 181.2^{bc}	ChCl:Gly + OD + UMAE	14713.3 ± 170.6^{bc}	ChCl:AA + FD + MAE	14385.0 ± 274.6^{ab}	Ethanol + FD + MAE	13893.3 ± 267.8^{ab}
ChCl:LA + VD + MAE	15039.7 ± 238.0^{bc}	ChCl:Gly + VD + MAE	14594.3 ± 223.4^{bc}	ChCl:AA + VD + MAE	14168.3 ± 139.8^{bc}	Ethanol + VD + MAE	13793.3 ± 194.8^{bc}
ChCl:LA + FD + UAE	14958.7 ± 213.6^{bc}	ChCl:Gly + FD + UAE	14417.7 ± 270.9^{cd}	ChCl:AA + OD + MAE	14011.7 ± 183.2^{bc}	Ethanol + OD + MAE	13650.0 ± 165.3^{bc}
ChCl:LA + OD + MAE	14873.0 ± 202.7^{cd}	ChCl:Gly + OD + MAE	14411.0 ± 169.7^{cd}	ChCl:AA + FD + UAE	13772.0 ± 228.7^{cd}	Ethanol + VD + UAE	13270.0 ± 181.6^{cd}
ChCl:LA + VD + UAE	14616.3 ± 199.2^{de}	ChCl:Gly + VD + UAE	14164.3 ± 162.0^{de}	ChCl:AA + VD + UAE	13715.0 ± 172.2^{cd}	Ethanol + FD + UAE	13242.3 ± 219.3^{cd}
ChCl:LA + FD + Conve	14474.7 ± 269.1^{e}	ChCl:Gly + FD + Conve	13817.7 ± 239.0^{e}	ChCl:AA + FD + Conve	13428.3 ± 285.0^{de}	Ethanol + FD + Conve	12983.3 ± 271.7^{de}
ChCl:LA + OD + UAE	14219.7 ± 203.7^{ef}	ChCl:Gly + OD + UAE	13701.0 ± 206.8^{ef}	ChCl:AA + OD + UAE	13248.3 ± 174.4^{e}	Ethanol + OD + UAE	12823.3 ± 158.9^{e}
ChCl:LA + VD + Conve	14099.7 ± 203.1^{f}	ChCl:Gly + VD + Conve	13507.7 ± 194.0^{f}	ChCl:AA + VD + Conve	13055.0 ± 197.6^{ef}	Ethanol + VD + Conve	12470.0 ± 210.2^{f}
ChCl:LA + OD + Conve	13906.3 ± 192.8^{f}	ChCl:Gly + OD + Conve	13427.7 ± 163.5^{f}	ChCl:AA + OD + Conve	12966.7 ± 200.3^{f}	Ethanol + OD + Conve	12412.0 ± 190.0^{f}

Note: Results were expressed as mean ± standard error of the mean (SEM). P values < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, f, denote significant differences from each other at $p < 0.05$.

Fruits like banana, dragon fruit, and peach exhibited lower antioxidant capacities, while the highest antioxidant capacity was determined in grapefruit peel as 10.79 ± 0.56 mg AAE/g with the ABTS test, followed by mango (9.32 ± 0.24 mg AAE/g), kiwi (8.95 ± 0.18 mg AAE/g), and avocado (7.19 ± 0.72 mg AAE/g) (Suleria, Barrow, & Dunshea, 2020). In this current study, it is shown that the enhanced efficiency is linked to the synergistic effects of microwave heating and ultrasonic cavitation, promoting better solvent penetration and phenolic antioxidant release.

11.2. DPPH Assay

The DPPH assay was used to determine the antioxidant activity of yellow nectarine peel extracts, which varied significantly across different solvent systems, drying methods, and extraction procedures. Among the tested methods, the NADES solvent ChCl: LA outperformed other solvents like ethanol and ChCl: Gly and, when combined with freeze-drying and ultrasound–microwave-assisted extraction, yielded the highest antioxidant efficiency at 9809.7 ± 176.5^{a}μmol TE/100 g DW. Between the phenolic compounds and the solvents, the enhanced hydrogen-bonding interactions are linked with extraction efficiency. The mango, avocado, and grapefruit peels, demonstrating higher capacities with polyphenols, are primarily responsible for the DPPH scavenging activity. The freeze-drying process gives redox-active metabolites and improved antioxidant capacity of peels compared to fresh

ones (Suleria et al., 2020). DPPH• radical values for oven-dried samples exhibited variability between 2,233 and 4,153 µmol TE per 100 g for peels (Martín-Diana et al., 2025b).

Table 5. DPPH assay of yellow nectarine peel at different extraction conditions.

Extraction Conditions	DPPH	Extraction Conditions	DPPH	Extraction Conditions	DPPH	Extraction Conditions	DPPH
ChCl:LA+ FD +UMAE	9809.7 ± 176.5^{a}	ChCl:Gly+ FD +UMAE	9321.3 ± 203.2^{a}	ChCl:AA+ FD +UMAE	8903.7 ± 186.8^{a}	Ethanol+ FD +UMAE	8404.0 ± 189.0^{a}
ChCl:LA+ FD +MAE	9387.0 ± 164.1^{b}	ChCl:Gly+ FD +MAE	9005.0 ± 139.6^{b}	ChCl:AA+ FD +MAE	8482.7 ± 150.3^{b}	Ethanol+ FD +MAE	8252.0 ± 109.1^{b}
ChCl:LA+ VD +UMAE	9356.0 ± 206.5^{b}	ChCl:Gly+ VD +UMAE	8904.7 ± 223.3^{bc}	ChCl:AA+ VD +UMAE	8463.7 ± 205.0^{b}	Ethanol+ VD +UMAE	8127.3 ± 204.3^{bc}
ChCl:LA+ OD +UMAE	9156.0 ± 123.5^{c}	ChCl:Gly+ OD +UMAE	8798.0 ± 133.8^{c}	ChCl:AA+ OD +UMAE	8387.0 ± 155.7^{bc}	Ethanol+ OD +UMAE	8037.3 ± 151.3^{c}
ChCl:LA+ VD +MAE	9009.3 ± 138.8^{cd}	ChCl:Gly+ VD +MAE	8640.7 ± 129.8^{cd}	ChCl:AA+ VD +MAE	8312.7 ± 136.6^{c}	Ethanol+ VD +MAE	7972.0 ± 144.2^{cd}
ChCl:LA+ FD +UAE	8965.3 ± 202.0^{cd}	ChCl:Gly+ OD +MAE	8604.0 ± 131.6^{cd}	ChCl:AA+ OD +MAE	8269.3 ± 128.9^{c}	Ethanol+ OD +MAE	7935.0 ± 118.3^{cd}
ChCl:LA+ OD +MAE	8962.7 ± 104.7^{cd}	ChCl:Gly+ VD +UAE	8542.3 ± 128.1^{d}	ChCl:AA+ VD +UAE	8222.7 ± 115.9^{cd}	Ethanol+ VD +UAE	7935.3 ± 139.4^{cd}
ChCl:LA+ VD +UAE	8866.0 ± 150.8^{de}	ChCl:Gly+ FD +UAE	8481.0 ± 186.6^{de}	ChCl:AA+ FD +UAE	8108.7 ± 255.5^{d}	Ethanol+ FD +UAE	7809.0 ± 203.4^{d}
ChCl:LA+ OD +UAE	8626.0 ± 152.4^{ef}	ChCl:Gly+ OD +UAE	8231.7 ± 147.8^{ef}	ChCl:AA+ OD +UAE	7856.0 ± 155.1^{e}	Ethanol+ OD +UAE	7458.7 ± 152.2^{e}
ChCl:LA+ VD +Conve	8423.0 ± 162.5^{fg}	ChCl:Gly+ VD +Conve	8012.3 ± 159.4^{f}	ChCl:AA+ VD +Conve	7625.0 ± 181.4^{f}	Ethanol+ FD +Conve	7217.3 ± 121.3^{f}
ChCl:LA+ FD +Conve	8339.0 ± 179.0^{g}	ChCl:Gly+ FD +Conve	7931.3 ± 127.2^{fg}	ChCl:AA+ FD +Conve	7547.0 ± 151.0^{f}	Ethanol+ VD +Conve	7192.0 ± 165.1^{f}
ChCl:LA+ OD +Conve	8333.0 ± 172.3^{g}	ChCl:Gly+ OD +Conve	7915.7 ± 162.3^{g}	ChCl:AA+ OD +Conve	7495.0 ± 171.2^{f}	Ethanol+ OD +Conve	7068.7 ± 149.4^{f}

Note: Results were expressed as mean ± standard error of the mean (SEM). P values < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, f, denote significant differences from each other at $p < 0.05$.

Antioxidant activity ranks as UMAE > MAE > UAE > conventional extraction across solvents under different extraction conditions, as shown in Table 5, which presents the DPPH content for the peel. Traditional extraction produced the lowest DPPH values compared to microwave-assisted extraction (MAE). Microwave heating and ultrasound cavitation improve cell wall rupture and mass transfer, enhancing antioxidant capabilities associated with UMAE and MAE. As with the ABTS assay, due to the preservation of sensitive phenolic components during drying methods, freeze-dried samples demonstrated superior DPPH scavenging abilities compared to vacuum-dried and oven-dried samples. Slower diffusion rates and restricted solvent penetration give conventional extraction methods the least antioxidant activity, hindering effective extraction from plant tissues.

11.3. FRAP Assay

The study evaluates the antioxidant capacity with the ferric reducing antioxidant power (FRAP) assay of yellow nectarine peel extracts using various procedures and techniques. The highest FRAP value was recorded for ChCl: LA + FD + UMAE at 11833.0 ± 195.6^{a}µmol TE/100 g DW, while, due to the poor extraction efficiency, the lowest value, 8830.7 ± 218.7^{h}µmol TE/100 g DW, resulted from Ethanol + OD + Conventional. The results highlight that NADES solvents, such as ChCl: LA, combined with freeze-drying, enhance antioxidant extraction and preserve antioxidants, with FRAP values diminishing under vacuum- and oven-drying methods. Table 6 shows the FRAP content for the peel under different extraction conditions. In the study by Martín-Diana et al. (2025b), freeze-drying also yielded higher Fe2+ values, ranging from 2,950 to 5,830 µmol Fe2+ per 100 g, compared to 1,278 to 2,030 µmol Fe2+ in oven-dried samples.

DPPH, FRAP, and CUPRAC assays confirmed that "Morsiani90" had the maximum antioxidant potential based on the findings reported by Mihaylova, Popova, Desseva, Manolov, et al. (2021) and Mihaylova, Popova, Desseva, Petkova, et al. (2021). The highest antioxidant potential was shown in the "Morsiani90" mango peel extract, surpassing the antioxidant activity of the whole fruit's methanolic extract due to its phenolic compounds. The DPPH test shows antioxidant values ranging from 30.09 to 276.28 µM/100 g fresh weight (fw), while the ABTS technique reports the highest value for "Evmolpiya" (749.67 µM), followed by "Flat Queen" (665.61 µM) and "Morsiani90" (433.89 µM) per 100 g fw. In the current study, UMAE reached the highest FRAP value during freeze-drying at 11833.0 ± 195.6^{a} µmol TE/100 g DW using ChCl: LA, while other solvents, such as ethanol, ChCl: Gly, and ChCl: AA, showed similar performance trends, indicating that hybrid extraction methods enhance solvent accessibility to bound phenolic compounds and improve mass transfer. Conversely, conventional extraction consistently resulted in the lowest FRAP values, highlighting its inefficacy in extracting antioxidant compounds.

Table 6. FRAP assay of yellow nectarine peel at different extraction conditions.

Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)
ChCl:LA + FD + UMAE	11833.0 ± 195.6^{a}	ChCl:Gly + FD + UMAE	11327.7 ± 197.6^{a}	ChCl:AA + FD + UMAE	10927.0 ± 205.4^{a}	Ethanol + FD + UMAE	10360.3 ± 223.6^{a}
ChCl:LA + FD + MAE	11316.3 ± 240.2^{b}	ChCl:Gly + VD + UMAE	10921.0 ± 151.6^{b}	ChCl:AA + VD + UMAE	10533.7 ± 153.6^{b}	Ethanol + FD + MAE	10217.0 ± 208.0^{ab}
ChCl:LA + VD + UMAE	11349.7 ± 168.0^{b}	ChCl:Gly + FD + MAE	10797.7 ± 245.0^{b}	ChCl:AA + FD + MAE	10217.0 ± 209.6^{c}	Ethanol + VD + UMAE	10013.7 ± 171.3^{b}
ChCl:LA + FD + UAE	10978.7 ± 202.4^{c}	ChCl:Gly + OD + UMAE	10607.7 ± 194.4^{c}	ChCl:AA + OD + UMAE	10190.3 ± 168.7^{c}	Ethanol + OD + UMAE	9738.3 ± 173.0^{c}
ChCl:LA + OD + UMAE	11059.7 ± 154.7^{c}	ChCl:Gly + FD + UAE	10471.0 ± 236.5^{cd}	ChCl:AA + FD + UAE	9948.7 ± 185.5^{cd}	Ethanol + FD + UAE	9505.7 ± 193.5^{d}
ChCl:LA + VD + MAE	10893.0 ± 181.0^{cd}	ChCl:Gly + VD + MAE	10407.7 ± 214.3^{cd}	ChCl:AA + VD + MAE	9910.3 ± 200.7^{cd}	Ethanol + VD + MAE	9417.0 ± 200.6^{de}
ChCl:LA + FD + Conve	10552.0 ± 214.0^{de}	ChCl:Gly + VD + UAE	10177.7 ± 170.5^{de}	ChCl:AA + OD + MAE	9747.0 ± 138.0^{de}	Ethanol + OD + MAE	9333.7 ± 176.3^{e}
ChCl:LA + VD + UAE	10593.0 ± 189.6^{de}	ChCl:Gly + OD + MAE	10174.3 ± 151.5^{de}	ChCl:AA + VD + UAE	9637.0 ± 153.2^{e}	Ethanol + OD + UAE	9223.7 ± 135.4^{ef}

Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)	Treatment	FRAP (µmol TE/100 g DW)
ChCl:LA + OD + MAE	10576.3 ± 187.3^{de}	ChCl:Gly + FD + Conve	9978.3 ± 223.4^{e}	ChCl:AA + OD + UAE	9544.3 ± 139.4^{e}	Ethanol + VD + UAE	9183.7 ± 200.2^{f}
ChCl:LA + OD + UAE	10446.3 ± 180.7^{e}	ChCl:Gly + OD + UAE	9937.7 ± 136.0^{e}	ChCl:AA + VD + Conve	9387.0 ± 197.6^{f}	Ethanol + OD + Conve	9133.7 ± 141.0^{fg}
ChCl:LA + VD + Conve	10185.3 ± 175.0^{f}	ChCl:Gly + VD + Conve	9787.7 ± 172.1^{f}	ChCl:AA + FD + Conve	9322.0 ± 238.6^{f}	Ethanol + VD + Conve	9024.3 ± 170.2^{g}
ChCl:LA + OD + Conve	10068.7 ± 194.1^{f}	ChCl:Gly + OD + Conve	9634.3 ± 120.8^{f}	ChCl:AA + OD + Conve	9250.3 ± 113.6^{f}	Ethanol + FD + Conve	8830.7 ± 218.7^{h}

Note: Results were expressed as mean ± standard error of the mean (SEM). P values < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, f, g, h, denote significant differences from each other at $p < 0.05$.

Significant differences were found between the freeze-drying and oven-drying processes for ABTS•+ radical values, with freeze-dried samples ranging from 4541 to 9268 µmol TE per 100 g and oven-dried samples ranging from 2,387 to 4,012 µmol TE per 100 g ($p < 0.05$) (Martín-Diana et al., 2025a). Further research on enzyme-assisted extraction and ultrasonic radiation for mango peels, conducted by Sharif, Bhatti, Bull, and Bilal (2023), achieved a maximum phenolic content of 33.56 ± 1.04 mg GAE/g and an optimal TEAC of 215.42 ± 1.21 mM TE/g. The antioxidant activity of yellow-fleshed nectarine peels was enhanced through acid-based deep eutectic solvents such as ChCl: LA, showing that freeze-drying combined with ultrasonic methods optimizes extraction while preserving bioactive compounds.

The research investigates the phenolic compounds present in the peel of yellow-fleshed nectarines, illustrating their enhanced antioxidant activity. Freeze-drying maintains a higher bioactive content and antioxidant capacity compared to other drying methods. This effectiveness arises from its low-temperature operation, which minimizes isomerization and degradation of phenolic compounds, and the creation of porous structures that enhance solvent penetration into the biomass (Stramarkou, Oikonomopoulou, Panagiotopoulou, Papadaki, & Krokida, 2023). Plazzotta, Ibarz, Manzocco, and Martín-Belloso (2020) noted that dried peach by-products provide superior phenolic values due to structural advantages that enhance extraction efficiency.

11.4. Different Solvent Extract Based Extraction Yield

This study aims to determine the most effective solvents and extraction techniques, emphasizing the importance of EY determination among factors such as solvent type, moisture level, and extraction technique, which significantly influence extraction efficiency and antioxidant capacity. Ethanol: water (8:2 v:v) and natural deep eutectic solvents (NADES) made of choline chloride with lactic acid, glycerol, and acetic acid (7:3) were selected for extracting various chemicals from fruit peel. In Table 7, the drying process, extraction method, and solvent type notably affected the yield of yellow nectarine peel extracts ($p < 0.05$), with yields varying from 15.9 ± 0.2% to 31.2 ± 0.7% using Equation 1.

The optimal extraction conditions were selected based on statistically significant differences among all treatment conditions, as determined by ANOVA and Tukey HSD post hoc tests ($p < 0.05$). Among the evaluated solvent-drying-extraction combinations, the ChCl: lactic acid solvent combined with freeze-drying and UMAE gives significantly higher phenolic recovery and antioxidant activity than the remaining treatments, demonstrating the statistical robustness of the optimization.

Table 7. Extraction yield of different solvent extracts at Ultrasound-assisted microwave extraction (UMAE), Microwave-assisted extraction (MAE), Ultrasound-assisted extraction (UAE), and Conventional extraction (CE).

Drying	Extraction	LA (%)	Gly (%)	AA (%)	EtOH (%)
FD	UMAE	31.2 ± 0.7^{a}	29.8 ± 0.6^{b}	27.6 ± 0.5^{c}	25.1 ± 0.6^{d}
FD	MAE	29.4 ± 0.6^{b}	28.1 ± 0.5^{c}	25.8 ± 0.6^{d}	23.5 ± 0.5^{e}
FD	UAE	27.6 ± 0.5^{c}	26.4 ± 0.6^{d}	24.2 ± 0.5^{e}	22.3 ± 0.4^{f}
FD	CE	25.5 ± 0.6^{d}	24.2 ± 0.5^{e}	22.6 ± 0.4^{f}	20.7 ± 0.4^{g}
VD	UMAE	28.4 ± 0.7^{c}	27.0 ± 0.6^{d}	24.9 ± 0.6^{e}	22.6 ± 0.5^{f}
VD	MAE	26.7 ± 0.6^{d}	25.5 ± 0.5^{e}	23.6 ± 0.5^{f}	21.4 ± 0.4^{g}
VD	UAE	24.8 ± 0.5^{e}	23.7 ± 0.6^{f}	21.9 ± 0.4^{g}	20.1 ± 0.3^{h}
VD	CE	22.9 ± 0.4^{f}	21.6 ± 0.4^{g}	19.8 ± 0.3^{h}	18.3 ± 0.3^{i}
OD	UMAE	25.1 ± 0.6^{d}	23.9 ± 0.5^{e}	21.7 ± 0.4^{f}	19.6 ± 0.4^{h}
OD	MAE	23.5 ± 0.5^{e}	22.4 ± 0.5^{f}	20.5 ± 0.4^{h}	18.9 ± 0.3^{i}
OD	UAE	21.8 ± 0.4^{f}	20.6 ± 0.4^{h}	18.9 ± 0.3^{i}	17.2 ± 0.3^{j}
OD	CE	20.1 ± 0.4^{h}	18.8 ± 0.3^{i}	17.3 ± 0.3^{j}	15.9 ± 0.2^{k}

Note: Results were expressed as mean ± standard error of the mean (SEM). P values < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, f, g, h, I, j, k, denote significant differences from each other at $p < 0.05$.

Freeze drying (FD) provides higher extraction yields attributed to better preservation of cellular structure, prevention of thermal decomposition, and improved solvent penetration than vacuum drying (VD) and oven drying (OD), with ultrasound–microwave-assisted extraction (UMAE) using lactic acid achieving the peak yield of 31.2 ± 0.7^{a}%. VD yielded 25.1 ± 0.6^{d}%, and OD yielded 28.4 ± 0.7^{c}%. Thermal degradation and structural collapse of plant tissues may reduce yield. Microwave-aided extraction (MAE) yielded 29.4 ± 0.6^{b}% in FD, outperforming VD (26.7 ± 0.6^{d}%) and OD (23.5 ± 0.5^{e}%). The extraction method significantly affected yields ($p < 0.05$), with UMAE being the most effective among all techniques. The yields ranked as UMAE > MAE > UAE > CE. The enhanced efficiency of UMAE is attributed to improving the mass transfer and solubilization of bioactive substances, combined with the mechanical and thermal effects of microwave heating and ultrasonic cavitation. Due to insufficient external energy for solvent penetration, the traditional extraction methods exhibited lower efficiency. Solvent choice also notably influenced extraction yields ($p < 0.05$), with FD solvents yielding: choline chloride with lactic acid (31.2 ± 0.7^{a}%) > glycerol (29.8 ± 0.6^{b}%) > acetic acid (27.6 ± 0.5^{c}%) > ethanol (25.1 ± 0.6^{d}%). In UMAE vacuum-dried samples, yields matched FD results with the same solvents.

The extraction techniques play a crucial role in determining the extraction efficiency of bioactive compounds while influencing energy consumption and industrial feasibility. From this study, it is concluded that the extraction efficiency from plant matrices is significantly influenced by the choice of solvent, with lactic acid and glycerol being effective 'green' solvents due to their high polarity and ability to hydrogen bond with phenolic compounds. In contrast, ethanol is less effective, yielding the lowest extraction of phenolics from nectarine peel. This study reveals important interactions between solvent type, extraction method, and drying technique, noting that extending the extraction time can enhance yield by increasing the solvent's interaction with the material. Previous studies corroborate that longer processing times improve the release of phenolic compounds through the increased permeability of matrix tissues due to ultrasound cavitation (da Silva Donadone et al., 2020; Setyaningsih, Saputro, Carrera, & Palma, 2019).

The combination of freeze-drying and ultrasound-microwave-assisted extraction (UMAE) using lactic acid yielded an optimal extraction of 31.2 ± 0.7^{a}% while the traditional method using ethanol and oven-drying resulted in a low yield of 15.9 ± 0.2^{k}%. Microwave heating rapidly increases the internal temperature and pressure, while ultrasonic cavitation enhances solvent penetration and disruption of the cell wall. From an energy-assisted extraction perspective, microwave extraction operates at high power for a shorter extraction time, which lowers the energy requirement, while ultrasonic probe extraction requires moderate amplitude and moderate temperatures, reducing thermal exposure. Reducing processing time and solvent consumption often lowers the operational cost, leading to a sustainable extraction process. Combining these two methods, UMAE gives better results than other

techniques with freeze-drying and ChCl: LA solvent. The research underscores the importance of selecting the right solvent, extraction methodology, and drying technique to optimize extraction efficiency, highlighting freeze-drying with lactic acid as the most effective combination.

12. REPRODUCIBLE (QUENCHER)ANTIOXIDANT CAPACITY ASSAYS

12.1. Q-TPC

With Q-TPC values of 5454.0 ± 28.8 mg GAE/100 g DW, freeze-dried yellow nectarine peel showed a much greater total phenolic content. The high concentration of phenolic compounds in peels is due to the accumulation of phenolic compounds linked to fruit color and antioxidant defense, which is found there. These results verify that, among yellow nectarine by-products, the freeze-dried yellow nectarine peel is the primary source of total phenolic content.

12.2. Q-DPPH

Yellow nectarine peel demonstrated more DPPH radical-scavenging activity, with Q-DPPH values of 12764.7 ± 116 µmol TE/100 g DW. The peel's higher concentration of phenolic compounds and flavonoids, which readily donate hydrogen atoms to neutralize DPPH radicals, is consistent with its higher antioxidant activity. The findings indicate that the main source of DPPH-based antioxidant qualities in dried yellow nectarine by-products is the yellow nectarine peel.

12.3. Q-ABTS•+

With Q-ABTS values of 17815.3 ± 178 µmol TE/100 g DW, freeze-dried yellow nectarine peel demonstrated a much greater ABTS•+ radical-scavenging ability. The peel's larger concentration of phenolic components, which may effectively quench the ABTS radical cation, accounts for its increased ABTS•+ scavenging action. The matrix's similar standard deviations show good analytical repeatability. Overall, the results show that among dried yellow nectarine by-products, peel is the main source of ABTS•+-based antioxidant qualities.

12.4. Q-FRAP

With a Q-FRAP value of 15578.7 ± 238 µmol TE/100 g DW, freeze-dried yellow nectarine peel exhibited a substantially greater ferric-reducing antioxidant capacity than the pomace. Because the peel contains more phenolic compounds that could effectively donate electrons in the FRAP experiment, it has a higher reducing capacity. The overall results show that freeze-dried peel is the main source of FRAP-based antioxidant activity among yellow nectarine by-products. Table 8 shows the Reproducible (QUENCHER) Antioxidant Capacity Assays.

Table 8. Direct Solid-State Antioxidant Capacity Assays.

Sample	Treatment	Q-TPC (mg GAE/100 g DM)	Q-DPPH (µmol TE/100 g DW)	Q-FRAP (µmol TE/100 g DW)	Q-ABTS•+ (µmol TE/100 g DW)
Peel	Dried	5454.0 ± 28.8	12764.7 ± 116.4	15578.7 ± 238.4	17815.3 ± 178.3

Martín-Diana et al. (2025b) state that Q-ABTS•+ and Q-DPPH• tests were used to assess the direct antioxidant capability of the various cultivars' by-products. Significant differences ($p < 0.05$) were found in the Q-ABTS•+ assay results for the peels (14,416 to 22,017 µmol TE 100 g−1) and kernels (19,143 to 28,333 µmol TE 100 g−1); no significant differences ($p < 0.05$) were found for the pulps (12,844 to 17,092 µmol TE 100 g−1). However, the Q-DPPH• test results showed significant differences ($p < 0.05$) between the various varieties for each type of by-product, with values ranging from 5926 to 9144 µmol TE 100 g−1 for the peels, from 8,462 to 12,319 µmol TE 100 g−1 for the kernels, and from 1907 to 3696 µmol TE 100 g−1 for the pulps.

13. STORAGE STABILITY OF NECTARINE PEEL EXTRACT

The study examines the stability of total flavonoid content (TFC) and total phenolic content (TPC) in ChCl: LA + FD + UMAE extract over 60 days under different storage conditions. 2389 mg GAE/100 g DW was the initial TPC. With a low reduction to 2229 mg GAE/100 g DW, storage at −20°C proved to be the most beneficial. On the other hand, TPC was significantly degraded by light exposure at 25°C, falling to 2135 mg GAE/100 g DW. Intermediate values were observed at 4°C and 25°C in darkness (2196 and 2176 mg GAE/100 g DW, respectively). Temperature- and light-induced oxidation, polymerization, and degradation of phenolic compounds were identified as the causes of the TPC reduction, with statistically significant variations ($p < 0.05$) seen throughout storage times. Figure 2 (a-g) shows the yellow nectarine peel extract under different storage conditions. TFC showed a similar pattern, beginning at 896 mg QE/100 g DW. TFC retention peaked at −20°C (821 mg QE/100 g DW), but exposure to light at 25°C reduced TFC to 734 mg QE/100 g DW.

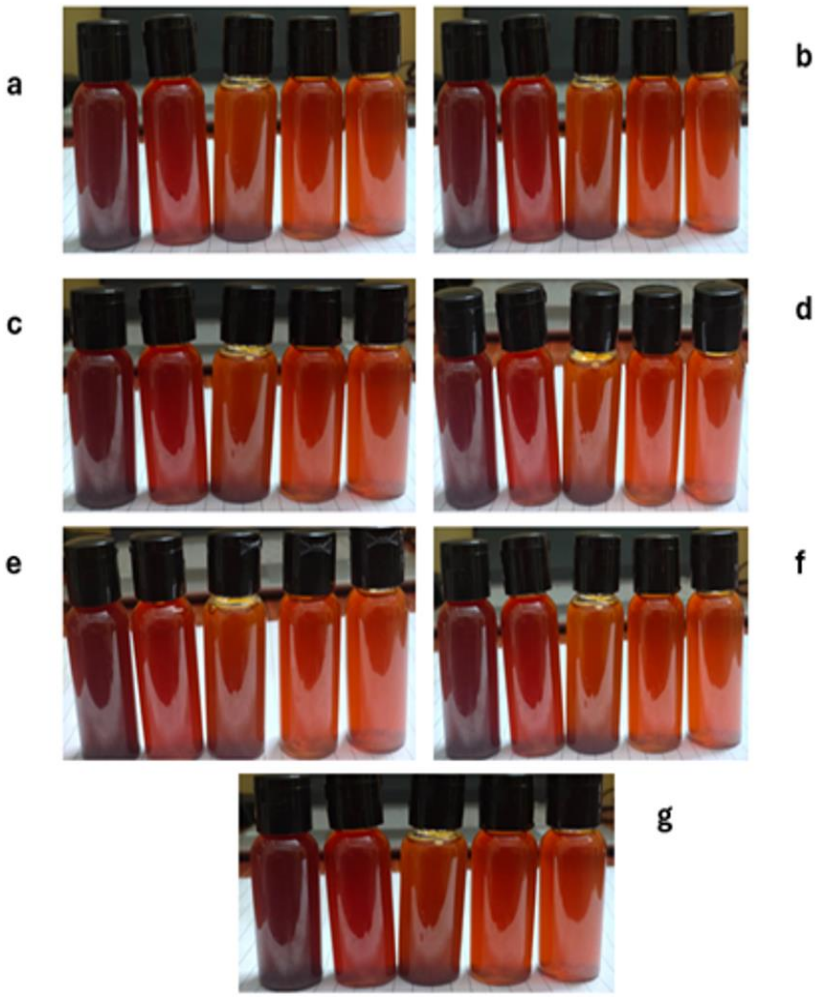

Figure 2 (a-g). Yellow nectarine peel extract under different storage conditions.

The intermediate retention values (795 and 771 mg QE/100 g DW, respectively) of samples kept at 4°C and in the dark highlighted the considerable vulnerability of flavonoids to oxidative destruction. The study also assessed the extract's DPPH radical-scavenging activity, which decreased with time and under different storage circumstances. It began at 9809.7 µmol TE/100 g DW and decreased under all conditions, with the greatest loss shown at 25°C with light exposure.

FRAP activity showed a decrease in electron-donating capacity that correlated with the breakdown of phenolic and flavonoid chemicals, mirroring the DPPH trends. After 60 days, ABTS radical-scavenging activity decreased

equally across circumstances, from 15819.7 µmol TE/100 g DW to lower levels. Figure 3(a-e) illustrates a multipanel graph showing the TPC, TFC, DPPH, ABTS, and FRAP parameters for different storage-conditioned peel extracts. Antioxidant activity is mainly supported by phenolic and flavonoid compounds, as demonstrated by the high association between TPC, TFC, DPPH, FRAP, and ABTS values.

Table 9 shows the storage stability of optimized peel extract under different storage conditions for TPC, TFC, DPPH, FRAP, and ABTS. The breakdown of reductive antioxidants, particularly flavonoids and phenolic acids, which transfer electrons to reduce ferric ions, is associated with a decrease in antioxidant activity. Higher temperatures accelerate oxidation and molecular degradation, while exposure to light encourages photochemical processes that further diminish the effectiveness of antioxidants. The results show that maintaining phytochemical stability and antioxidant capability in phenolic-rich plant extracts requires low temperature and light protection.

Table 9. Storage stability for optimized peel extract for different storage conditions for TPC, TFC, DPPH, FRAP, ABTS.

Storage time (days)	**-20**	**4**	**25 (dark)**	**25 (light)**	
0	2389.0 ± 35.8^{a}	2389± 35.8^{a}	2389± 35.8^{a}	2389± 35.8^{a}	TPC (mg GAE/100 g DW)
15	2355± 20.8^{b}	2339± 21.6^{b}	2311± 24.2^{b}	2291± 22.6^{b}	
30	2312±15.5^{c}	2291±17.5^{c}	2253±19.6^{c}	2235±17.4^{c}	
45	2278± 23.3^{d}	2244± 21.3^{d}	2215± 20.5^{d}	2173± 19.3^{d}	
60	2229± 18.0^{e}	2196± 19.0^{e}	2176± 18.5^{e}	2135± 20.1^{e}	
Storage time (days)	-20	4	25 (dark)	25 (light)	
0	896± 20.3^{a}	896± 20.3^{a}	896± 20.3^{a}	896± 20.3^{a}	TFC (mg QE/100 g DW)
15	880.13± 17.5^{b}	870.19± 15.8^{b}	853.19± 18.5^{b}	836± 16.4^{b}	
30	862.33±18.4^{c}	849.43±19.2^{c}	833.73±17.7^{c}	809±16.4^{c}	
45	840± 21.4^{d}	824± 20.3^{d}	804± 19.5^{d}	774± 18.3^{d}	
60	821± 19.3^{e}	795± 18.7^{e}	771± 17.4^{e}	734± 16.5^{e}	
Storage time (days)	-20	4	25 (dark)	25 (light)	
0	9809.7 ± 175.8^{a}	9809.7 ± 175.8^{a}	9809.7 ± 175.8^{a}	9809.7 ± 175.8^{a}	DPPH (µmol TE/100 g DW)
15	9770.87± 177.5^{b}	9745.67± 167.6^{b}	9704.17± 166.4^{b}	9660.14± 169.3^{b}	
30	9718.73±169.5^{c}	9681.23±164.7^{c}	9626.61±166.3^{c}	9575.31±170.3^{c}	
45	9640.27± 167.6^{d}	9591.47± 165.7^{d}	9533.47± 167.6^{d}	9474.47± 165.4^{d}	
60	9535.67± 164.5^{e}	9487.24± 167.4^{e}	9411.54± 162.8^{e}	9330.54± 165.4^{e}	
Storage time (days)	-20	4	25 (dark)	25 (light)	
0	11833 ± 195^{a}	11833 ± 195^{a}	11833 ± 195^{a}	11833 ± 195^{a}	FRAP (µmol TE/100 g DW)
15	11782± 187.5^{b}	11741± 185.8^{b}	11691± 186.3^{b}	11626± 184.6^{b}	
30	11709.3±189.5^{c}	11655.37±187.8^{c}	11594.67±184.8^{c}	11506.17±187.6^{c}	
45	11581.3± 197.4^{d}	11520.13± 196.4^{d}	11486.43± 193.6^{d}	11390.73± 196.3^{d}	
60	11493.6± 189.7^{e}	11425.26± 183.6^{e}	11360.66± 185.5^{e}	11241.61± 184.7^{e}	
Storage time (days)	-20	4	25 (dark)	25 (light)	
0	15819.7 ± 184.5^{a}	15819.7 ± 184.5^{a}	15819.7 ± 184.5^{a}	15819.7 ± 184.5^{a}	ABTS (µmol TE/100 g DW)
15	15666.3 ± 180.9^{b}	15606.3 ± 180.9^{b}	15494.3 ± 185.5^{b}	15354.3 ± 187.4^{b}	
30	15456.3 ± 185.3^{c}	15386.3 ± 185.3^{c}	15306.3 ± 185.3^{c}	15176.3 ± 188.3^{c}	
45	15213.0 ± 183.6^{d}	15083.0 ± 183.6^{d}	15005.0 ± 188.4^{d}	14915.0 ± 185.7^{d}	
60	15016.3 ± 196.2^{e}	14866.3 ± 196.2^{e}	14706.3 ± 192.4^{e}	14576.3 ± 196.4^{e}	

Note: Results were expressed as mean ± standard error of the mean (SEM). P values < 0.05 were regarded as significant. Results with different superscripts, that is, a, b, c, d, e, denote significant differences from each other at $p < 0.05$.

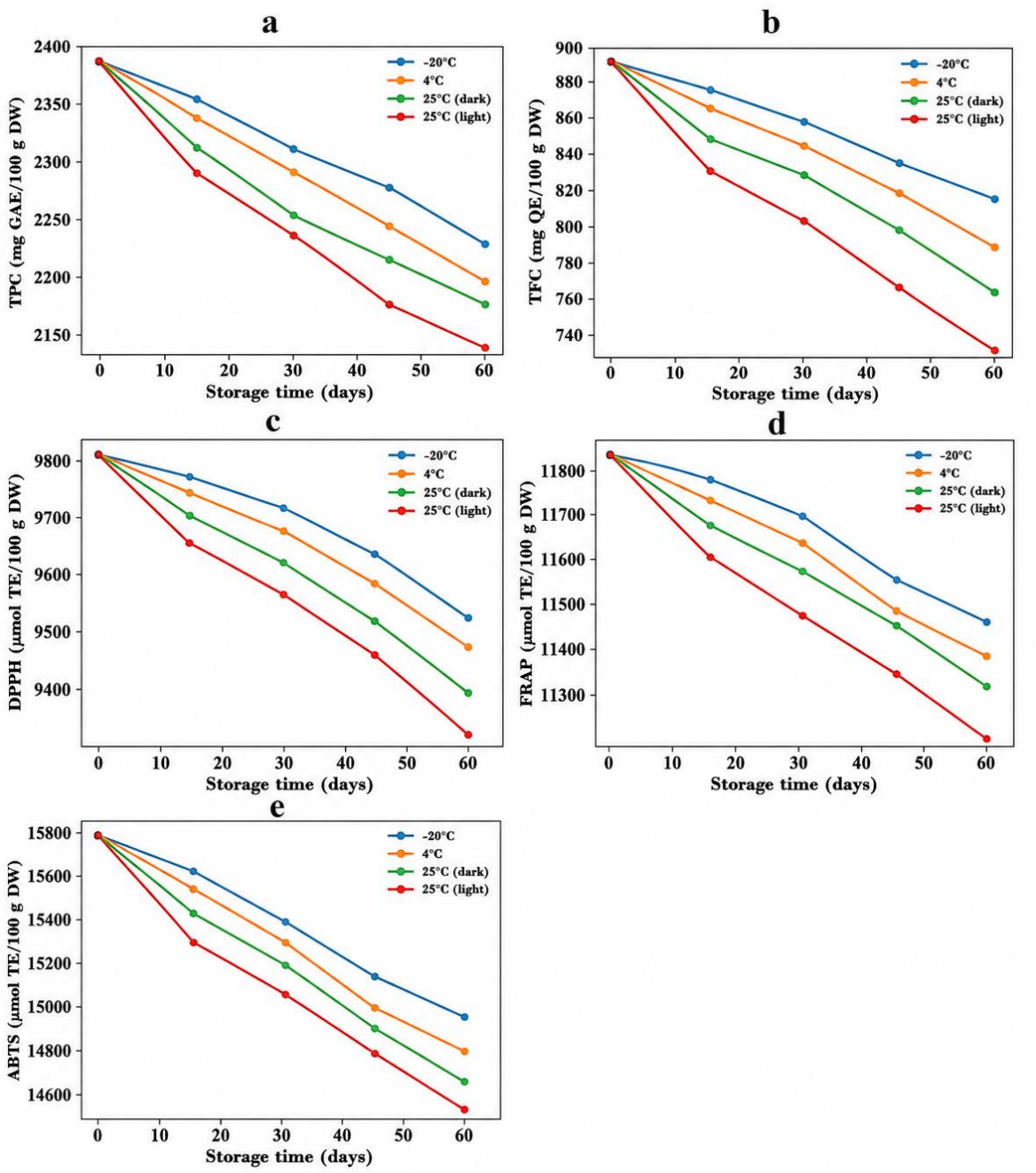

Figure 3 (a-e). A multipanel graph for TPC, TFC, DPPH, ABTS, and FRAP for different storage-conditioned peel extracts.

The best storage settings for preserving greater levels of TPC, TFC, and antioxidants were found to be −20°C, whereas exposure to light at 25°C led to the greatest losses. This highlights the necessity of proper storage conditions for the long-term quality maintenance of these extracts.

13.1. Pearson's Correlation Analysis

Total phenolic content (TPC), total flavonoid content (TFC), and antioxidant activity, determined by DPPH, FRAP, and ABTS tests in the ChCl: LA + FD + UMAE extract throughout storage, were evaluated using Pearson correlation analysis. The substantial relationship between phytochemical content and antioxidant ability was highlighted by the correlation matrix, which showed extremely significant positive correlations ($p < 0.001$) across all parameters. TPC and TFC had a very good association ($r = 0.987^{***}$), indicating that flavonoids make up a significant portion of the extract's phenolic constituents.

Furthermore, TPC showed excellent relationships with FRAP (r = 0.993***), DPPH (r = 0.986***), and ABTS (r = 0.988***), underscoring the critical function of phenolic compounds in antioxidant activity, with FRAP activity showing the highest link. With correlations of DPPH (r = 0.991***), FRAP (r = 0.993***), and ABTS (r = 0.979***), TFC also showed good associations with the antioxidant tests, demonstrating the importance of flavonoids in electron donation and free radical-scavenging activities. The diagonal values (r = 1.000), which indicate self-correlation, were not considered when interpreting the correlations between the variables. Table 10 showed the Pearson correlation coefficients between the yellow nectarine peel extract's TPC, TFC, FRAP, DPPH, and ABTS during storage.

Table 10. Pearson correlation coefficients between the yellow nectarine peel extract's total phenolic content (TPC), total flavonoid content (TFC), ferric reducing antioxidant power (FRAP), DPPH radical scavenging activity, and ABTS radical scavenging activity during storage.

Parameters	TPC	TFC	DPPH	FRAP	ABTS
TPC	1	0.987***	0.986***	0.993***	0.988***
TFC		1	0.991***	0.993***	0.979***
DPPH			1	0.996***	0.991***
FRAP				1	0.993***
ABTS					1

Note: Pearson's correlation coefficients (r) are represented as values. At $p < 0.001$, *** denotes significance.

Previous research by Floegel, Kim, Chung, Koo, and Chun (2011) supports these findings, suggesting that the ABTS assay is more effective than the DPPH assay for evaluating the antioxidant capacity of hydrophilic and lipophilic fruits. The existence of other non-flavonoid antioxidants engaged in ABTS neutralization may be indicated by the somewhat reduced correlation between TFC and ABTS. DPPH and FRAP exhibited the greatest association (r = 0.996***) among the antioxidant tests, suggesting that the chemicals responsible for hydrogen donation in DPPH were similarly efficient in ferric ion reduction, as determined by FRAP. Additionally, strong correlations between FRAP and ABTS (r = 0.993***) and DPPH and ABTS (r = 0.991***) were observed, indicating a consistent reflection of antioxidant compound breakdown throughout storage. Figure 4 shows the heatmap of Pearson correlation coefficients among TPC, TFC, FRAP, DPPH, and ABTS of yellow nectarine peel extract during different storage conditions.

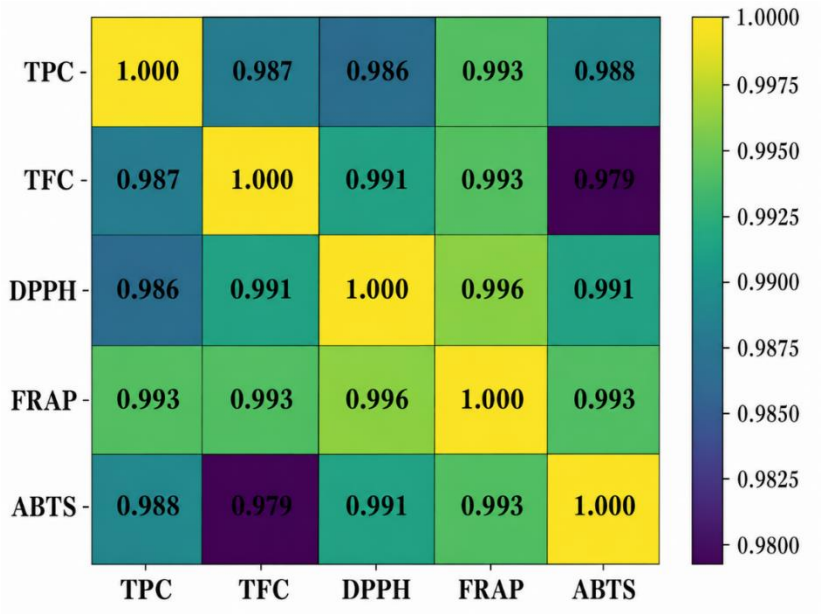

Figure 4. Heatmap of Pearson correlation coefficients among total phenolic content (TPC), total flavonoid content (TFC), ferric reducing antioxidant power (FRAP), DPPH radical scavenging activity, and ABTS radical scavenging activity of yellow nectarine peel extract throughout storage.

According to a prior investigation, FRAP and other antioxidant tests showed considerable favorable relationships (Suleria et al., 2020). The persistently significant positive correlations between phytochemicals and antioxidant activities indicate that the breakdown of phenolic and flavonoid contents because of oxidative and photooxidative processes is the main cause of the reduction in antioxidant potential during storage. Concurrent decreases in TPC, TFC, DPPH, FRAP, and ABTS levels result from this deterioration. Overall, the extract's phenolic and flavonoid compounds were identified by the Pearson correlation analysis as the major sources of antioxidant activity, highlighting the need to preserve phytochemical components to sustain antioxidant functioning throughout storage.

14. INDUSTRIAL IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTION

Peels are recommended as an excellent possibility due to their high levels of bioactive compounds and antioxidant activity in commercial uses, with consumer choices and preferences. Peels may be used as flavor enhancers, for the production and development of natural colorants for minimally processed and newly developed products such as flavored curd, yogurt, puree, concentrated juices, and baked goods. The compositions may improve immune systems as well as mouthfeel, shelf life, and functional claims.

Despite the encouraging results from this current study, the limitations should also be acknowledged. This study was done using only one cultivar, and the phytochemical profiling may vary from cultivar to cultivar, harvesting season, maturity stage, geographical region, and post-harvest handling. The extraction experiments were performed at a laboratory scale. For commercial purposes, an industrial environment is needed to perform solvent recycling, continuous processing, and energy consumption, and production cost was not evaluated. Storage stability was also evaluated under selected conditions, which may vary on an industrial scale.

Future research should focus on validating the extraction strategy across different cultivars, climate conditions, and harvesting timings to improve the robustness of this current study. Advanced metabolic profiling should be performed to observe biological activities. A study on bioaccessibility, bioavailability, and in vivo biological effects of the extract is required for future implications for commercial uses to improve consumer acceptance. Due to the biodegradable and low-toxicity nature of NADES solvents, industrial implementations are required to perform a pilot-scale study where sustainable manufacturing practices are emphasized. With further optimization of solvent recovery, process integration, and scale-up, the proposed extraction strategy has considerable potential for commercial implementation.

15. CONCLUSION

A competent, greener method was explored for extracting anthocyanins and assessing antioxidant activity using four NADES solvents constituted of choline chloride with glycerol, acetic acid, and lactic acid, as well as one traditional solvent (ethanol), from yellow nectarine. The highest total phenolic content (2389.0 ± 35.8^a mg GAE/100 g DW), total flavonoid content (896.0 ± 19.7^a mg QE/100 g), and antioxidant activities, including 15819.7 ± 183.7^a µmol TE/100 g DW (ABTS), 9809.7 ± 176.5^a µmol TE/100 g DW (DPPH), and 11833.0 ± 195.6^a µmol TE/100 g DW (FRAP), were obtained with the NADES solvent (ChCl: LA+FD+UMAE), followed by the performances of the other solvents. It is thought that the increased concentration of phenolic chemicals in exterior tissue (peel) is related to their primary natural role, which is defense against infections and environmental stress.

Overall, the combination of NADES with UMAE provides a highly efficient, energy-saving, and potentially scalable green extraction approach for the sustainable recovery of bioactive compounds from the peel. This study established that yellow nectarine peels, as a byproduct, might be beneficially utilized commercially for the development of value-added food products, as well as nutraceuticals. A stability study showed that heat and light

sensitivity occurred during the post-extraction process. A future techno-economic assessment and pilot study are needed for the byproduct of yellow nectarine peel for future commercial applications.

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