

Evaluation of the Chemical Composition and Antioxidant Capacity of Dried Orange Pulp

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ABSTRACT

The disposal of orange juice by-products presents an environmental challenge due to their high volume and accumulation in landfills. Valorizing these residues supports the development of a circular economy within the agro-industrial sector, offering both environmental and economic benefits. This study aimed to valorize orange juice processing residues by producing a dried orange pulp (DOP) flour and characterizing its physicochemical and phytochemical properties to assess its potential suitability as a sustainable feed ingredient for broiler chickens. The physicochemical properties of the sun-dried and finely milled orange by-products (<1 mm) were analyzed using standard methods, including proximate composition analysis (moisture, ash, crude protein, crude cellulose), and spectrophotometric assays for phytochemicals (total phenolics, flavonoids, condensed tannins) and antioxidant activity [2,2-Diphenyl-1-picrylhydrazyl (DPPH), Ferric Reducing Antioxidant Power (FRAP)]. The DOP demonstrated high levels of dietary cellulose (89.19% Dry Matter), ash (3.81% Dry Matter), total phenolics (202.59 \pm 15.93 mg Gallic Acids Equivalent/100 g DM), total flavonoids (430.70 \pm 2.78 mg Quercetin Equivalent/100 g), and strong antioxidant activity (FRAP: 1158.8 \pm 19.22 mg/g). Phenolic profiling via High-Performance Liquid Chromatography (HPLC) revealed flavanones as the dominant subclass, with hesperidin (61.29 mg/g) and ferulic acid (27.1 mg/g) as major constituents. These results highlight the nutritional and functional potential of DOP as a feed additive. The remarkable antioxidant capacity and high concentration of bioactive compounds like hesperidin position DOP not just as a filler, but as a functional feed additive that could enhance animal health.

Keywords: Ferulic acid, Hesperidin, Hydrocinnamic acid, Orange waste

INTRODUCTION

Fruits and vegetables represent the highest food waste category globally, with estimated losses reaching approximately 45% of total production (Caldeira et al., 2019; Ortiz-Sanchez et al., 2024). Among these, citrus fruits stand out as one of the most cultivated and processed fruit groups worldwide, with an annual output exceeding 122.5 million tons, a significant portion of which is dedicated to juice production (Jiang et al., 2014). During processing, considerable quantities of citrus by-products are generated—particularly peel (flavedo) and rags (albedo)—which account for 45–60% of the whole fruit mass (Berk, 2016; Camacho et al., 2023).

Citrus processing generates substantial quantities of by-products, including peels, pulps, and seeds, which are typically discarded despite their richness in nutrients, dietary fiber, and bioactive phytochemicals. The accumulation of these residues poses environmental and economic challenges for the agro-industrial sector. Nevertheless, the valorization of citrus by-products has recently attracted significant interest within the framework of circular economy strategies, aiming to transform waste materials into value-added resources. Several studies have demonstrated that orange by-products contain higher concentrations of functional compounds than the edible portions of the fruit, particularly polyphenols and flavonoids known for their potent antioxidant properties. Quantitative analyses have shown considerable variation in the total phenolic content (TPC) of orange by-products. For instance, Castro et al. (2020) reported a value of 534 \pm 30 mg gallic acid equivalents (GAE)/100 g dry matter (DM), while Escobedo-Avellaneda et al. (2014) found 650 \pm 90 mg GAE/100 g DM in lyophilized whole orange samples (juice, flavedo, and albedo). Conversely, Danesi et al. (2018) recorded a lower TPC of 450 \pm 30 mg GAE/100 g DM in orange albedo. Based on these findings, the orange by-product flour (OBPF) evaluated in the present study exhibited a higher phenolic content than that reported for flours derived from other fruit peels, underscoring its potential as a natural source of antioxidants for applications in feed and food formulations. Moreover, the antioxidant potential of the orange by-product flour (OBPF), evaluated using the FRAP and ORAC assays, was found to be 93 \pm 5 μ mol TE/100 g DM and 11,728 \pm 541 μ mol TE/100 g DM, respectively. The antioxidant activity showed a strong relationship with the TPC, indicating that higher

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concentrations of phenolic compounds contributed to greater antioxidant capacity in the flour. Comparable findings were reported for orange by-product (albedo) obtained from juice production, which exhibited a FRAP value of 49.7 ± 0.3 $\mu\text{mol TE/g DM}$ (Castro et al., 2020). Similarly, Escobedo-Avellaneda et al. (2014) determined an ORAC value of $11,953 \pm 538$ $\mu\text{mol TE/100 g DM}$ in their study assessing the phytochemical composition and antioxidant potential of various orange parts. These results confirm that the phenolic richness of OBPF plays a crucial role in its reducing and radical-scavenging capacities, reinforcing its suitability as a natural antioxidant source.

In this context, transforming citrus byproducts into functional ingredients is considered a viable approach to addressing the dual challenges of waste management and sustainable nutrition. Despite being rich in nutrients, dietary fiber, and bioactive compounds, these residues are frequently treated as waste, posing significant environmental burdens for the industry. The disposal of citrus waste, primarily through landfilling and uncontrolled dumping, leads to the generation of greenhouse gases, particularly methane, due to the anaerobic decomposition of its high organic load. Furthermore, the high moisture content (around 80-90%) and biodegradability of this waste result in leachate production, which can contaminate soil and groundwater with organic acids and other phytotoxic compounds (Zema et al., 2022).

Different studies have shown that orange juice residues can be utilized in animal feed (Bampidis and Robinson, 2006). Moreover, in a recent feeding trial, the effects of replacing yellow corn with orange peel by-product (OP) in broiler diets were demonstrated that chicks receiving the control and OP15 diets exhibited superior final body weights and feed conversion ratios compared with those fed higher inclusion levels. Additionally, the OP20 group showed a reduction in total serum cholesterol relative to the control, and all experimental treatments enhanced economic efficiency. Collectively, these findings indicate that orange peel by-product can replace up to 15% of yellow corn in broiler diets without compromising growth performance, highlighting its potential as a nutritionally viable and cost-effective feed ingredient (Dilek et al., 2025). Research indicated that various forms of orange waste, including dried pulp (Agu et al., 2010) and peel extracts (Pourhossein et al., 2015; Seidavi et al., 2015), can be effectively incorporated into poultry diets. Studies on broilers and laying hens showed that appropriate inclusion levels up to 15-20% for pulp (Agu et al., 2010), and 1000 mg/L for extract (Pourhossein et al., 2015; Seidavi et al., 2015) can improve performance metrics such as body weight and feed conversion ratio (Seidavi et al., 2015; Ciftci et al., 2016). Furthermore, these by-products positively influence carcass quality by reducing abdominal fat and liver weight (Ebrahimi et al., 2014; Abbasi et al., 2015), enhance immune response by increasing immunoglobulin and white blood cell counts (Pourhossein et al., 2015), and improve blood lipid profiles by lowering cholesterol and triglycerides (Nazok et al., 2010; Ciftci et al., 2016). These by-products positively influence carcass quality by reducing abdominal fat and liver weight, enhancing immune response by increasing immunoglobulin and white blood cell counts, and improving blood lipid profiles by lowering cholesterol and triglycerides. Moreover, these byproducts were used in the production of essential oils (Sahraoui et al., 2011). However, the objective of this study was to develop and characterize a flour derived from dried orange juice by-products, and to evaluate its potential inclusion in broiler chicken diets as a cost-effective and functional feed additive.

MATERIALS AND METHODS

Ethical approval

The work was conducted under the general institutional biosafety authorization ESA/GLP-2021/03 issued by the Higher School of Agronomy, Mostaganem, Algeria.

Preparation

Orange juice co-products (peels, pulp, and seeds) from *Citrus sinensis* (sweet orange) were collected fresh from a local citrus juice processing facility located in Chlef, Algeria. The materials were dried in a passive solar greenhouse dryer at $35-45$ °C for 48-72 hours, until the moisture content decreased below 10%, verified by weight monitoring and oven-drying at 105 °C (Özcan et al., 2021). Adequate ventilation was ensured using natural airflow and solar-powered fans to prevent microbial growth. The dried material was subsequently milled, passed through a 1 mm sieve, and stored in airtight, light-resistant polyethylene bags at $20-25$ °C in a clean and ventilated environment (Readh et al., 2023).

Proximate composition analysis

The proximate composition of the powdered orange juice co-products was determined through standard procedures to quantify dry matter, moisture content, and ash content. Moisture determination was conducted by oven-drying the samples at 105 °C for 24 hours (Özcan et al., 2021). The dry matter and moisture content were calculated using the following equations (AOAC, 2005).

$$\text{Dry Matter (\%)} = \text{Mass (Dry Matter) (g)}/\text{Mass (sample) (g)} \times 100 \text{ (Formula 1)}$$

$$\text{Water content (g. 100g₁Sample)} = 100 - \text{Dry Matter (\%)} \text{ (Formula 2)}$$

To determine ash content (mineral matter), the previously dehydrated samples were incinerated in a muffle furnace at 550 °C for 3 hours until a constant white ash was obtained (Ebouel et al., 2023). The content of mineral matter (MM) was calculated using the following formula.

$$\text{Mineral Matter (MM \%)} = (M_2 - M_0) / (M_1 - M_2) \times 10 \quad (\text{Formula 3})$$

The mineral matter (MM) content of the samples was determined using a gravimetric method (AOAC, 2005). The mass of the empty crucible was recorded as M_0 (g), followed by the mass of the crucible containing the test sample, denoted as M_1 (g). After incineration and cooling, the mass of the crucible and the remaining raw minerals was measured as M_2 (g). The mineral matter content was then calculated and expressed as grams per 100 grams of the sample (g/100 g).

Crude cellulose content

Crude cellulose content was analyzed using the Weende method (Ebouel et al., 2023). The sample was sequentially digested with hot acid and alkali, isolating cellulose. This residue was incinerated to remove organic matter. Cellulose was calculated by using Formula 4 (AOAC, 2005).

$$\text{Cellulose content} = (P_1 - P_2) / P_0 \times 100 / \text{Dry Matter (Formula 4)}$$

where P_0 represents the weight of the test sample (g), P_1 is the weight of the crucible with the residue before incineration (g), and P_2 is the weight of the crucible with the residue after incineration (g). DM denotes the dry matter content (%).

Protein content

Protein content in the powdered orange juice co-products was determined using the Lowry method, as outlined by Satpathy et al. (2020). A sample aliquot was homogenized in 25 mL of chilled physiological saline, filtered, and diluted. From the prepared dilution, 1 mL of the sample was mixed with the Lowry reagent and allowed to react for 10 minutes. Afterward, a diluted Folin–Ciocalteu reagent (Sigma-Aldrich, USA) was added, followed by vortexing. The reaction mixture was then kept at 4 °C in the dark for 30 minutes to complete color development. The absorbance was recorded at 700 nm using a UV–Visible spectrophotometer (SPECORD 210, Germany). Protein concentration was determined using a bovine serum albumin (BSA) standard curve and expressed as a percentage of dry matter.

Extraction of bioactive compounds

A 20 g powdered sample was mixed with 200 mL of methanol and agitated on an orbital shaker (Edmund Bühler GmbH, KS-15, Hechingen, Germany) at 450 rpm for 24 hours at 23 ± 1 °C in darkness to prevent photodegradation. The extract was filtered and stored in amber flasks. The extract was used for antioxidant assays (2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2'-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid (ABTS) and for quantifying total phenolics, flavonoids, and condensed tannins via validated spectrophotometric methods (Gargouri et al., 2013).

Quantification of phenolic compounds

Total phenolic content

The TPC was determined using the Folin–Ciocalteu colorimetric assay as described by Jaradat et al. (2015). In brief, 1 mL of the sample extract was combined with diluted Folin–Ciocalteu reagent (Sigma-Aldrich, USA) and 4 mL of sodium carbonate solution (75 g/L; Sigma-Aldrich, USA). The reaction mixture was incubated at room temperature for 1 hour, after which the absorbance was measured at 765 nm using a spectrophotometer. Total phenolic concentration was calculated from a gallic acid calibration curve (10-100 µg/mL) and expressed as milligrams of gallic acid equivalents per gram of dry extract (mg Gallic Acid Equivalent/g Dry Extract).

Total flavonoid content

The aluminum chloride colorimetric method was used to indicate total flavonoid content (Pertiwi et al., 2020). Equal volumes of extract and 2% AlCl₃·6H₂O (Sigma Aldrich, United States) were incubated for 10 minutes at room temperature, and absorbance was read at 430 nm. Results were expressed in mg quercetin equivalent per gram of dry extract (mg QE/g DE), after the use of quercetin standard curve (0-60mg/L).

Condensed tannins

Condensed tannin content was determined using the vanillin assay as described by Agbo et al. (2015). Briefly, 1.5 mL of concentrated sulfuric acid (Sigma-Aldrich, USA) and 3 mL of 4% vanillin solution prepared in methanol were added to 50 mL of the diluted extract. The mixture was incubated for 15 min at room temperature in the dark, after which absorbance was measured at 500 nm. The results were expressed as milligrams of catechin equivalents per 100 grams of dry matter (mg Catechin Equivalent/100 g Dry Matter), using a catechin calibration curve ranging from 0 to 400 µg/mL ($R^2 = 0.999$).

Antioxidant activity and phenolic compound characterization

Free radical scavenging assay by 2,2-diphenyl-1-picrylhydrazyl (DPPH)

The antioxidant activity of the orange by-product extract was assessed using the DPPH radical scavenging assay, following the reported method of [Mohamadi *et al.* \(2023\)](#). The DPPH radical scavenging activity was determined following the standard procedure. Briefly, 0.1 mL of the methanolic extract (31.25-500 µg/mL) was mixed with 2 mL of 0.4% DPPH solution prepared in ethanol. The mixture was vigorously shaken and incubated in the dark at 30 °C for 30 min. The absorbance was then measured at 517 nm, and the percentage of inhibition was calculated relative to the control. The percentage of radical inhibition was calculated using Formula 5 ([Chewchinda *et al.*, 2021](#)).

$$\text{IP (\%)} = (\text{Ac-As})/\text{Ac} \times 100 \text{ (Formula 5)}$$

(IP): Inhibition percentage, (Ac) is the absorbance of the control, and (As) is the absorbance of the sample.

Radical scavenging assay by 2,2'-Azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS)

The ABTS radical scavenging capacity was determined following the procedure described and modified by [Mohamadi *et al.* \(2023\)](#). The ABTS•⁺ radical cation was generated by combining 7 mM ABTS solution with 2.45 mM potassium persulfate (Sigma-Aldrich, United States) and allowing the mixture to stand in the dark at 25 °C for 12-16 h. The resulting stock solution was then diluted with ethanol until its absorbance reached 0.70 ± 0.02 at 734 nm. Subsequently, 20 µL of the sample extract or Trolox standard was added to 2 mL of the ABTS•⁺ working solution. After incubation for 6 min at 30 °C, the absorbance was recorded at 734 nm. The antioxidant potential was expressed as Trolox Equivalent Antioxidant Capacity (TEAC), and measurements were performed at three different concentrations.

Identification and quantification of phenolic compounds

The phenolic composition of the orange by-product extract was determined through high-performance liquid chromatography coupled with diode array detection (HPLC-DAD/UV), as described by [Maalej *et al.* \(2022\)](#) with minor modifications. The analysis was performed using an Agilent 1260 system (Germany) equipped with an Eclipse DB C18 column (4.6 × 250 mm, 5 µm particle size). The mobile phase consisted of 0.1% acetic acid in water (solvent A) and acetonitrile (solvent B), applied under a gradient program as follows: 10% B for 0-22 min, 50% B for 22-32 min, 100% B for 32-44 min, followed by a return to 10% B at 44-50 min. The flow rate was maintained at 0.5 mL/min, with an injection volume of 5 µL, and the column temperature was set at 40 °C. UV-Vis spectra were monitored from 190 to 400 nm, while detection was carried out at 254, 280, and 330 nm to identify distinct groups of phenolic compounds.

Statistical analysis

The experiment was independently repeated five times on separate days using freshly prepared materials to obtain five biological replicates (n = 5). This approach accounts for the expected biological and procedural variability inherent in the experimental process. All analyses were subsequently performed on these five independent samples. Results are expressed as mean ± standard deviation (SD). Descriptive statistical methods were applied to evaluate data consistency and variability. Where applicable, statistical significance between groups was determined using a one-way analysis of variance (ANOVA) followed by a post-hoc Tukey test for multiple comparisons. All statistical analyses were performed using IBM SPSS Statistics version 26, and a p-value of less than 0.05 was considered statistically significant.

RESULTS AND DISCUSSION

Biochemical composition of dried orange pulp

The proximate biochemical composition of dried orange juice by-products is summarized in Table 1. These by-products contained low levels of fat and protein, moderate amounts of dietary cellulose, and a pH of approximately 6.10. Such characteristics suggest that this material can be incorporated as a fibrous and mildly acidic feed ingredient that supports normal digestive function in poultry. Moderate fiber levels enhance gut motility, while a slightly acidic environment promotes enzymatic activity and nutrient absorption. Moreover, the acidic nature of the material may contribute to improved intestinal microbiota balance by reducing populations of *Enterobacteriaceae*, *Escherichia coli*, and *Staphylococcus* spp, while increasing beneficial *Lactobacillus* spp. in the small intestine of broilers ([Vlaicu *et al.*, 2020](#)).

The orange pulp analyzed in the present study contained 89.19% dry matter, 2.10% crude fat, 3.81% ash, and 5.50% crude protein. The crude protein content of the dried orange by-products analyzed in the present study is relatively low compared to conventional protein sources such as soybean meal or even cereal grains. This finding is consistent with the values previously reported by [Castro *et al.* \(2020\)](#), confirming that orange by-products are poor in nitrogenous compounds. Consequently, their incorporation into poultry diets should not aim to supply protein but rather to provide an

alternative energy and fiber source. Aside from being used as an alternative feed ingredient to replace energy sources, fruit peel meal as a feed ingredient in broiler rations is often used as a functional feed ingredient (Sugiharto et al., 2018). This is related to the presence of various active ingredients in fruit peel meal, such as antimicrobial, antioxidant, anti-inflammatory, immunomodulatory, and other components. Despite their modest protein content, dried orange pulp is characterized by a high concentration of readily fermentable carbohydrates, pectin, and bioactive compounds such as flavonoids and limonene, which can promote intestinal health, antioxidant status, and overall performance in broiler chickens. These values were higher than those reported by El-Beltagi et al. (2022) for crude fat and protein contents. Furthermore, the ash concentration was markedly elevated compared with the findings of Castro et al. (2020), while the protein level remained relatively comparable. The moisture content of the oven-dried orange peel powder was 11.35%, which is in close agreement with the results reported by Özcan et al. (2021) and consistent with the observations of the current study, 10.81.

Table 1. Chemical composition of dried orange by-products (g.100g⁻¹DM)

Parameter	Dried orange pulp
pH	6.10 ± 0.01
Aw (g.100g ⁻¹ DM)	10.81 ± 1.44
Dry Matter (g.100g ⁻¹ DM)	89.19 ± 1.44
Ash (g.100g ⁻¹ DM)	3.81 ± 0.09
Dietary Cellulose (g.100g ⁻¹ DM)	22.03 ± 1.89
Total fat (g.100g ⁻¹ DM)	2.10 ± 0.05
Crude Proteins (g.100g ⁻¹ DM)	5.50 ± 0.05

aw: Water activity. The results are expressed as means ± standard deviation

Phytochemical content and antioxidant capacity of dried orange pulp

The quantified levels of total polyphenols, flavonoids, and condensed tannins, together with antioxidant activities determined through DPPH and ABTS assays, are summarized in Table 2. These bioactive compounds are known to exert beneficial effects on animal performance and health by enhancing the secretion of endogenous digestive enzymes, saliva, bile, and mucus, thereby improving nutrient digestion and assimilation. In addition, their antioxidant and anti-inflammatory properties help to modulate gut morphology and reduce the population of pathogenic bacteria, while promoting beneficial microbiota balance (Juhari et al., 2021; Saleem et al., 2022). Several studies have further reported that higher growth rates and improved feed conversion ratios in poultry fed phenolic-rich diets result from increased intestinal surface area and enhanced digestive enzyme activity, which collectively facilitate better nutrient absorption (Ani and Abel, 2018; Maheshwari et al., 2022). Moreover, the bioactive compounds contributed to potential health-promoting properties (Diarra et al., 2018).

The results of this study revealed that dried orange pulp (DOP) contained a TPC of 202.59 mg Gallic Acid Equivalent/g Dry Extract and a total flavonoid content of 430.70 mg Quercetin Equivalent/g Dry Extract, confirming its richness in bioactive phytochemicals. Regarding flavonoid content, the results of the present study were comparable to those reported by Abou-Arab et al. (2016), who observed values ranging from 437.50 to 453.33 mg QE/100 g in microwave-dried mandarins, *Citrus valencia*, and *Citrus balady* pulp.

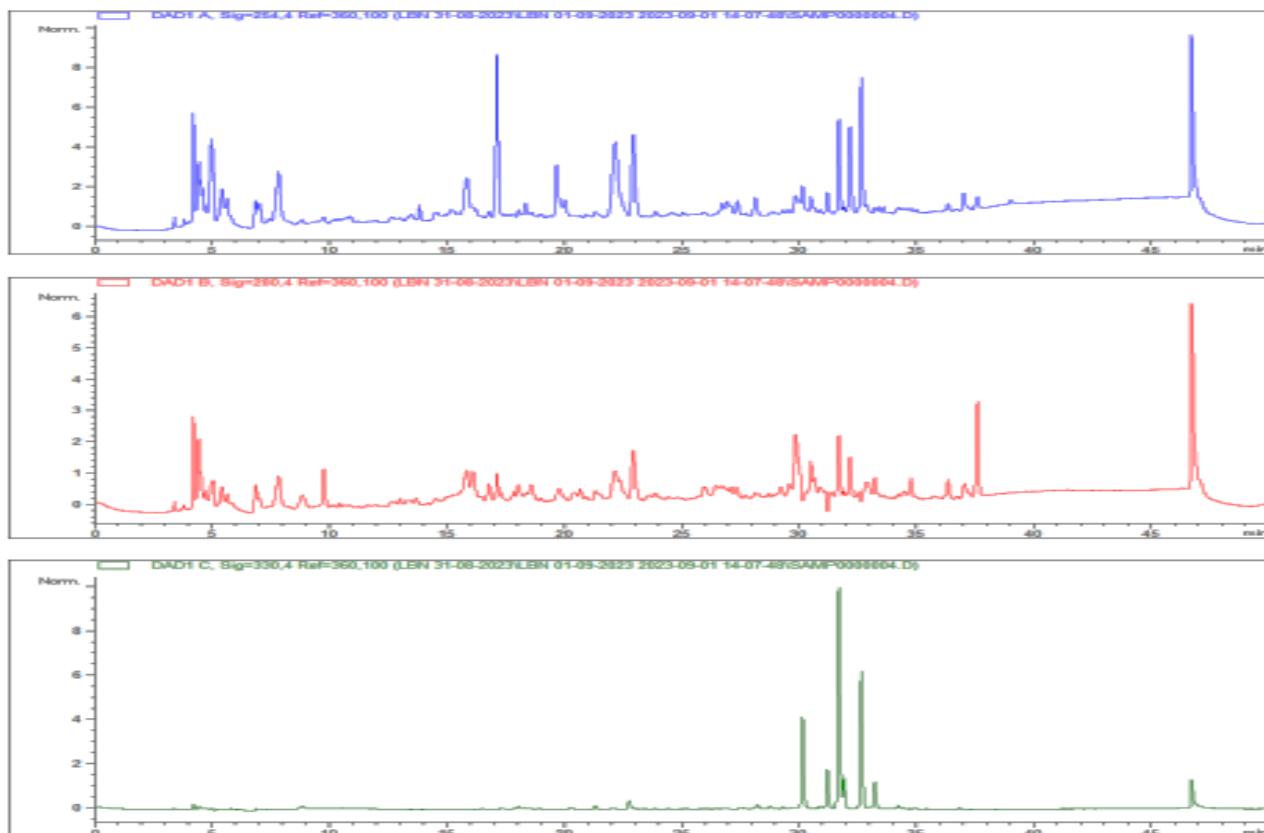
The TPC of the dried orange pulp obtained in this study was comparatively higher than that of orange and mandarin peels, which ranged from 169.54 to 178.90 mg GAE/100 g, and also exceeded the values reported for orange pulp (104.98–123.02 mg GAE/100 g) by Al-Juhaimi (2014). However, it remained below the 534 mg GAE/100 g reported by Castro et al. (2020).

The antioxidant capacity determined by the DPPH and ABTS assays reached 270.68 ascorbic acid /g Dry Extract and 1158.80 Trolox Equivalent Antioxidant Capacity/g dry Extract, respectively. The reducing power refers to the ability of DOP constituents to donate electrons to neutralize free radicals, thereby converting them into more stable and less reactive species. This strong electron-donating capacity highlights the potential of DOP as a natural antioxidant and functional feed additive in poultry nutrition. Moreover, the antioxidant activity (ABTS and DPPH assays) indicated a positive correlation with phenolic content, consistent with the findings of Barreca et al. (2014) and Papoutsis et al. (2016). The HPLC-DAD analysis identified a total of nineteen phenolic compounds in DOP, encompassing four flavonoids and spanning three main classes, including phenolic acids, flavanone glycosides, and flavanol glycosides (Figure 1 and Table 3). Furthermore, notable levels of quercetin (10.6 mg/g), rutin (0.4 mg/g), and epicatechin (7 mg/g)—members of the flavanol group—contributed significantly to the overall antioxidant potential of the extract. The chemical diversity and richness in both flavonoids and phenolic acids highlighted the nutritional value and functional bioactivity of dried orange pulp, supporting its application as a promising natural source of antioxidants.

Table 2. Phenolic compounds and antioxidant activity of the studied by-products (*Citrus Siensis*)

Parameter	Dried orange pulp
Phenolic compounds (mg GAE/g)	202.59 ± 15.93
Flavonoids (mg QE/g)	430.70 ± 2.78
Tannins (mg CE/g)	150.00 ± 18.03
ABTS (mg/g)	1158.8 ± 19.22
DPPH (mg/g)	270.68 ± 5.95

DPPH: 2,2-Diphenyl-1-picrylhydrazyl, ABTS: 2,2'-Azino-bis-3-ethylbenzothiazoline-6-sulfonic acid. The results are expressed as means ± standard deviations.

**Figure 1.** HPLC-DAD chromatograms of orange juice by-products recorded at 254, 280, and 330 nm**Table 3.** Phenolic compounds in orange pulp

RT	Component	mg/g	λ nm	Subclasses of Compounds
1	Caffeic acid	1.00	330	
2	Ferulic acid	27.1	280	Hydrocinnamic acids
3	p-Coumaric acid	0.3	280	
4	p-Hydroxybenzoic acid	1.31	254	
5	Vanillic acid	0.1	254	Hydrobenzoic acids
6	Dydimine	0.61	330	
7	Naringenin	0.2	280	
8	Narirutin	1.76	280	Flavonones
9	Hesperidin	61.29	330	
10	Hesperetin	0.3	280	
11	Luteolin	0.8	330	
12	Apigenin	0.8	254	Flavones
13	Rutin	0.4	330	
14	Quercetin	10.6	254	Flavanols
15	Epicatechin	7	280	
16	Quercitrin	4.2	254	
17	Protocatechuic acid	Trace	280	Phenolic acids
18	Chlorogenic acid	2.7	254	
19	Ascorbic acid	3.2	280	
T		123.67		

RT: Retention time; C: Concentration (mg/mL); λ nm: Wavelength; T: Total

The phenolic profiling of the dried orange by-product revealed that hesperidin, a predominant flavanone, was the most abundant compound (61.29 mg/g), followed by ferulic acid (27.10 mg/g), underscoring the notable presence of flavonoids and phenolic acids.

This high concentration of hesperidin is particularly relevant, as previous research on *Arbor Acres* broilers demonstrated that dietary supplementation with flavonoids, specifically genistein and hesperidin at inclusion levels of 5 mg/kg, 20 mg/kg, and a 1:4 mixture, significantly enhanced the chicken's antioxidant defense system. Supplemented broilers exhibited elevated serum total antioxidant capacity (T-AOC) and superoxide dismutase (SOD) activity, along with reduced malondialdehyde (MDA) concentrations, indicating improved oxidative stability. Additionally, hesperidin supplementation favorably influenced lipid metabolism, resulting in decreased total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), and triglyceride (TG) levels, as well as an enhanced polyunsaturated fatty acid (PUFA) profile and an optimized n-6/n-3 fatty acid ratio in breast muscle. Therefore, the high hesperidin content identified in the orange by-product suggests its potential contribution to similar antioxidant and hypolipidemic effects when incorporated into broiler diets (Kamboh et al., 2013).

The dehydrated orange pulp analyzed in the present study exhibited higher concentrations of caffeic acid (1.00 mg/g), ferulic acid (27.10 mg/g), and p-coumaric acid (0.30 mg/g) than those reported for kinnow peel by Rafiq et al. (2019). However, the concentrations of quercetin (10.6 mg/g), caffeic acid (1.00 mg/g), naringin (0.20 mg/g), and rutin (0.40 mg/g) were lower than the levels reported by Omoba et al. (2015) in orange peel extracts. The identification of hydroxycinnamic acids, namely caffeic, ferulic, and p-coumaric acids, corroborates the findings of De Ancos et al. (2017) and Ferreira et al. (2018), who reported similar phenolic profiles in orange pulp and mandarin peel methanolic extracts, respectively. The presence of naringenin, hesperidin, narirutin, and didymin in the analyzed orange pulp is consistent with the findings of De Ancos et al. (2017). Notably, the hesperidin content in the samples exceeded the concentrations reported by Chen et al. (2017) for two varieties of orange peel, which were 26.81 mg/g and 20.99 mg/g. Furthermore, the detected concentrations of hesperidin and naringin were in agreement with those reported in *Citrus reticulata* peel, ranging from 50.13 to 100.52 mg/g (Liu et al., 2013). Hesperidin was identified as the predominant compound, with levels surpassing those documented by Molina-Calle et al. (2015).

Related research indicated that incorporating an appropriate amount of ferulic acid into broiler feed can significantly improve growth performance (Shu et al., 2022). The beneficial effects of phenolic compounds such as quercetin, rutin, and hesperidin on broiler performance and health have been well established. Quercetin improves performance efficiency by modulating intestinal morphology and nutrient absorption (Samuel et al., 2017), while rutin supplementation enhances body weight gain and feed conversion ratio through its positive impact on gut structure and digestive functionality (Viveros et al., 2011). Similarly, hesperidin at 20 mg/kg diet was reported to promote intestinal health and stimulate immune responses in poultry (Hong et al., 2012). Beyond these physiological effects, citrus flavanones, including hesperetin and naringin, display notable antimicrobial activity against pathogens such as *Helicobacter pylori*, *Aeromonas hydrophila*, and *Staphylococcus aureus*, thereby contributing to improved feed efficiency and meat oxidative stability (Bakar et al., 2012; Goliomytis et al., 2015; Agus et al., 2017; Chen et al., 2018).

Flavones such as luteolin and apigenin, commonly found in glycosylated forms, are hydrolyzed by intestinal *Lactobacillus* species (e.g., *L. agilis*) to produce aglycones and metabolites with enhanced bioavailability (Panche et al., 2016). These compounds and their derivatives exert positive effects on gut integrity and performance, as evidenced by improved growth efficiency in chickens fed alfalfa-derived flavones (Changxing et al., 2018). Furthermore, luteolin exhibits strong antibacterial activity against antibiotic-resistant *Escherichia coli* strains (Ouyang et al., 2013), highlighting the multifunctional role of flavones in maintaining intestinal health and productivity in poultry.

In poultry, dietary phenolics such as ferulic and caffeic acids have been associated with enhanced growth performance, reduced lipid peroxidation, and improved gut health, thereby supporting overall animal welfare and productivity.

CONCLUSION

The chemical composition of orange waste demonstrates its promise as a valuable bioresource for diverse industrial and nutritional applications, although validation through *in vivo* studies remains necessary. Extraction using methanol resulted in the highest recovery of bioactive compounds, underscoring their efficiency compared to other solvents. The key findings demonstrated that DOP is rich in dietary fiber (22.03% DM) and possesses a remarkable phytochemical profile, including high levels of total phenolics (202.59 mg GAE/g), total flavonoids (430.70 mg QE/g), and potent antioxidant activity (FRAP: 1158.8 mg TE/g). The elevated phenolic content highlights the antioxidant potential of this material, with hesperidin identified as the major active compound. The HPLC analysis identified flavonoids as the dominant subclass, with hesperidin (61.29 mg/g) and ferulic acid (27.10 mg/g) as the major constituents. Further studies are recommended to explore large-scale extraction processes, evaluate bioavailability in animal and human systems, and

assess the synergistic effects of these compounds when incorporated into feed and food formulations within circular economy models.

DECLARATIONS

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Availability of data and materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Authors' contributions

Ahmed Readh Chaib Eddour contributed to Conceptualization, experimental design, data collection, statistical analysis, data interpretation, manuscript drafting, preparation of figures and tables, and final manuscript revision. Miloud Litim assisted in the experimental setup and contributed to data interpretation and manuscript review. Kaddour Bouderoua supervised the experimental procedures and ethical compliance, verification of analytical accuracy, and critical revision of the manuscript. The authors read and approved the last edition of the manuscript for publication.

Competing interests

The authors declare that there are no competing interests or conflicts of interest related to this work.

Ethical considerations

All ethical considerations related to this study, including but not limited to plagiarism, consent for publication, research misconduct, data fabrication or falsification, redundant publication, and simultaneous submission, have been thoroughly reviewed and addressed by all authors. The research was conducted in accordance with ethical standards and institutional guidelines. The authors confirm that no artificial intelligence (AI) tools were used in the conduct, analysis, or writing of this study.

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