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Orange Peel-Derived Carbon Dots for Anti-Aging Serum: Antioxidant and UV-Protective Potential

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Abstract: *Orange peel-derived carbon dots are nanoscale carbon materials with tunable physicochemical and optical properties, offering promising antioxidant and UV-absorbing capabilities for skincare application. This review examines their potential as functional ingredients in anti-aging facial serum, focusing on synthesis, characterization, antioxidant activity, UV-protective properties, and formulation considerations. Their 2,2-diphenyl-1-picrylhydrazyl radical-scavenging ability and UV-A and UV-B absorption, coupled with high visible-light transmittance, suggest potential to mitigate oxidative stress and UV-induced skin damage. Further research is essential to optimize serum formulation and comprehensively evaluate concentration dependent activity, skin compatibility, formulation stability, photostability, skin penetration, and long-term safety through rigorous experimental studies. Overall, orange peel-derived carbon dots offer a promising approach to integrating agricultural waste valorization with nanotechnology for sustainable skincare, although their practical anti-aging efficacy remains to be experimentally validated.*

Key Word*: Serum, orange peel, carbon dots, antioxidant, anti-aging.*

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I. Introduction

Carbon dots (CDs) are a class of fluorescent carbon-based nanomaterials typically smaller than 10 nm that exhibit unique optical and physicochemical properties including quantum dot-like behavior.[1-3] A characteristic feature of CDs is their ability to exhibit photoluminescence upon optical excitation, including excitation in the UV region.[4,5] Over the past two decades, CDs have attracted considerable attention because of their unique optical properties, potential biocompatibility, and the possibility of sustainable synthesis from renewable biomass-derived precursors.[6] These characteristics have created opportunities for their exploration in various biomedical and cosmetic applications, including potential use in skincare formulations.[7] Among various renewable resources, plant-derived biomass has emerged as an attractive carbon source for the green synthesis of CDs. Orange peel (OP), an abundant agricultural and food-processing by-product, is particularly promising because it contains vitamin C, flavonoids, phenolic compounds, and other naturally occurring bioactive constituents. Vitamin C, or L-ascorbic acid, is an essential water-soluble vitamin that plays important biological and physiological roles. It is also a well-known antioxidant and can contribute to the protection of biological systems against oxidative stress.[8,9] Orange peel-derived carbon dots (OP-CDs) can be prepared by carbonization of orange peel as a carbonaceous precursor.[10] Recent studies have reported that OP-CDs can exhibit UV absorption, antioxidant activity, photostability, and favorable biocompatibility, highlighting their potential for applications in skin-care formulations. Their antioxidant properties are particularly relevant to skin aging because oxidative stress is an important factor associated with skin damage and premature aging (**Figure 1**).[11] Skin oxidative stress is mainly associated with excessive generation of reactive oxygen species (ROS), which can interact with cellular components such as proteins, lipids, DNA, and organelles. Persistent oxidative damage may contribute to cellular senescence, disruption of the skin barrier, extracellular matrix degradation, inflammation, skin roughness, and other changes associated with premature skin aging.[12] Therefore, ingredients with effective ROS-scavenging and antioxidant properties are of considerable interest in the development of anti-aging skincare products.

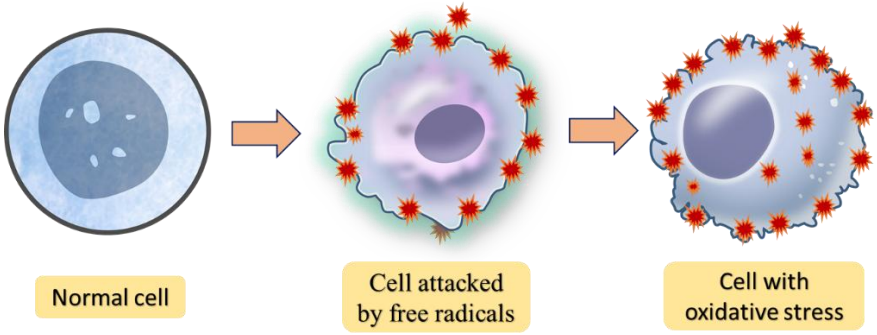


Figure 1. Oxidative stress of cell induced by free radical.

Carbon dots have demonstrated antioxidant activity that may be associated with their surface functional groups and their ability to interact with reactive species. These characteristics may help mitigate oxidative stress and reduce oxidative damage to biomolecules, suggesting a potential role for CDs in skin-protective and anti-aging applications.[13] However, the extent of these effects depends on the physicochemical characteristics, surface chemistry, concentration, and biological environment of the CDs. Plant-derived carbon dots offer a sustainable approach to developing carbon-based skincare ingredients from renewable biomass. Among these materials, OP-CDs are of particular interest because of their reported antioxidant and UV-absorbing properties, which warrant further investigation for potential applications in anti-aging facial serum.[14] Serums are lightweight skincare formulations designed to deliver active ingredients for targeted cosmetic benefits. In anti-aging skincare, serum formulations provide a suitable platform for incorporating functional ingredients that may help maintain skin hydration and protect against environmental stressors. Incorporating OP-CDs into facial serums could offer a potential approach to developing multifunctional skincare products. However, their formulation stability, skin compatibility, and actual anti-aging efficacy require further investigation.[15-18]
In this review, we focus on orange peel-derived carbon dots for anti-aging serum applications with particular emphasis on their antioxidant activity, UV-protective properties, and potential role in protecting the skin against oxidative stress and premature aging. The use of orange peel as a sustainable precursor may provide a promising route toward the development of nature-inspired and environmentally friendly anti-aging serum formulations.

II. Synthesis of Orange Peel-Derived Carbon Dots

Why Orange Peel

Orange peel is an abundant, inexpensive, renewable, and sustainable agro-food by-product that contains carbon-rich organic components, making it an attractive precursor for the green synthesis of carbon dots.[19] The use of biomass and food wastes as carbon sources provides a sustainable approach for converting low-value waste into functional nanomaterials while reducing waste generation and resource consumption.[20-22] In this context, orange peel offers a readily available and low-cost feedstock for the production of value-added carbon-based nanomaterials. Several studies have demonstrated the successful conversion of orange peel into fluorescent carbon dots through relatively simple and environmentally friendly synthesis routes. OP-CDs have shown desirable optical characteristics, including strong light absorption and fluorescence, supporting their potential use in optical and sensing applications.[23,24] More recently, OP-CDs prepared by a simple pyrolysis route exhibited strong UV absorption and effective UV-blocking performance, demonstrating the potential of orange peel as a precursor for UV-protective materials.[4] In addition to their optical and UV-related properties, biomass-derived CDs can exhibit significant antioxidant activity. For example, CDs prepared from vegetable wastes such as tea and grape residues showed radical-scavenging activity in 2,2-diphenyl-1-picrylhydrazyl (DPPH) and other antioxidant assays, demonstrating that waste-derived CDs can function as sustainable antioxidant materials.[6] More specifically, orange peel-derived carbon nanoparticles have also demonstrated substantial DPPH radical-scavenging activity, indicating that orange peel can serve as a promising precursor for antioxidant carbon nanomaterials.[25]The combination of antioxidant and UV-protective properties is particularly relevant to skincare applications because oxidative stress and ultraviolet radiation are important contributors to skin aging.[26,27] Carbon-based nanomaterials with antioxidant, UV-absorbing, and other functional properties have therefore attracted interest for potential applications in advanced skincare formulations.[28,29,14] However, most reported applications of OP-CDs have focused on areas such as sensing, packaging, and other functional materials rather than facial skincare, indicating an opportunity to explore their incorporation into anti-aging serum formulation.

Overall, orange peel represents a promising waste-derived carbon source for the sustainable synthesis of functional CDs. Its availability, low cost, and demonstrated ability to produce CDs with optical, antioxidant, and

UV-protective properties provide a strong scientific rationale for investigating orange peel-derived CDs as potential active ingredients in anti-aging facial serum formulations.[4,11,21,23]

Synthesis:

OP-CDs can be synthesized using different approaches, including (i) thermal, (ii) hydrothermal and (iii) electrochemical methods. These methods offer potential routes for converting orange peel waste into functional carbon nanomaterials for skincare applications.

(i) Thermal Synthesis of Orange Peel-Derived Carbon Dots

Orange peels are thoroughly washed with distilled water and dried to remove moisture. The dried peels are then carbonized at 250 °C for 10 h to obtain carbon-rich char.[30,25] This thermal conversion approach is consistent with broader strategies for producing carbon-based nanomaterials from biomass and natural precursors.[31,32] The resulting char is cooled to room temperature, ground into a fine powder, and treated with 10% (v/v) H_2O_2. Specifically, 25 g of char is mixed with 500 mL of H_2O_2 solution. The treated material is then dispersed in ultrapure water and sonicated at 25 °C for 30 min to facilitate particle dispersion. The resulting suspension is filtered through a 0.2-µm membrane and centrifuged at 20,000 × g for 30 min. The supernatant is collected and purified by dialysis against deionized water for 24 h. The purified carbon nanoparticles are then stored at 4 °C for subsequent characterization of their physicochemical and optical properties and evaluation of their antioxidant activity and biocompatibility.[25]

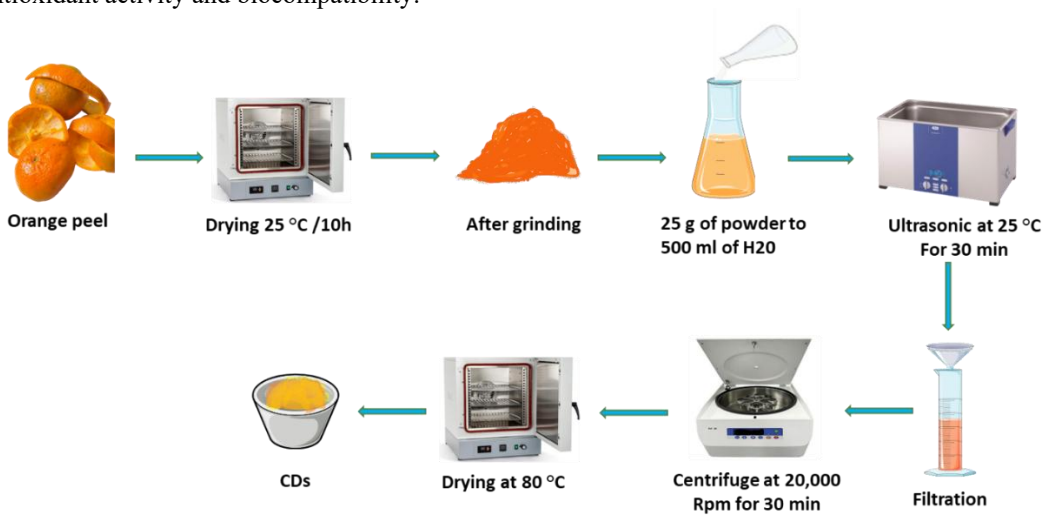


Figure 2. Synthesis of carbon dots from waste orange peel.

(ii) Hydrothermal Synthesis of Orange Peel-Derived Carbon Dots

Orange peels are first washed with water, dried in sunlight, and subsequently oven-dried at 150 °C for 10 h to obtain carbonized material. The dried orange peels are then treated with 100 mL of 0.1 M H_2SO_4, rinsed with water, filtered, and oven-dried at 150 °C for 2 h. Subsequently, the pretreated material is soaked in 60 mL of sodium hypochlorite (NaClO) solution at room temperature for 4 h and repeatedly washed with water until the pH of the washing water reaches 7. The oxidized orange peels are then dispersed in 25 mL of water and subjected to hydrothermal treatment in a Teflon-lined autoclave at 180 °C for 12 h. After natural cooling, the resulting brown solution is washed with dichloromethane to remove unreacted organic compounds. The aqueous phase is then centrifuged at 5,000 rpm for 15 min to separate it from the solvent and dried at 100 °C for 2 h to obtain the carbon dots **(Figure 3)**. The reported product yield is 12.3%, based on 2 g of raw orange peel waste, corresponding to 0.246 g of CDs.[33] Another study reported OP-CDs with a particle size of approximately 2-7 nm and a quantum yield of 12.7% using a hydrothermal synthesis approach.[34]

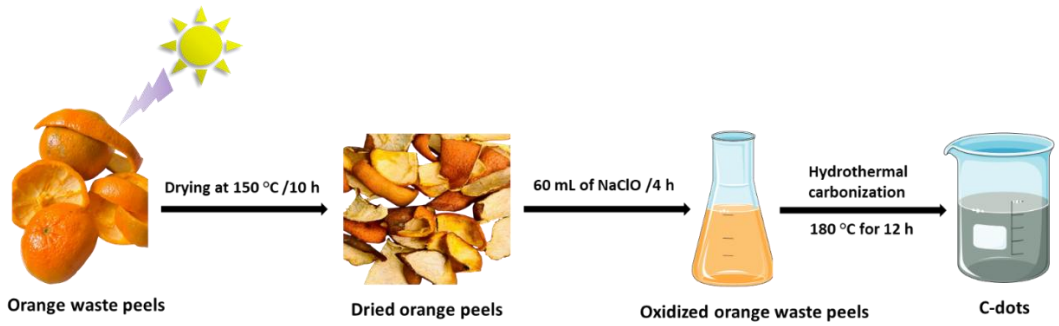


Figure 3. Formation of C-dots by using waste orange peels under hydrothermal treatment.

(iii) Electrochemical Synthesis of Orange Peel-Derived CDs

Orange peel waste can serve as a sustainable carbon source for the preparation of carbon dots by electrochemical synthesis approach **(Figure 4)**. The aqueous stream obtained from the hydrothermal carbonization of orange peel waste can be used as a precursor for the electrochemical bottom-up synthesis of carbon dots (step-1). In a typical procedure, 2.5 mL of the aqueous precursor (0.121 g mL^{-1}) is mixed with 2.5 mL of 30% ammonia solution in a glass vial (step-2). Electrochemical treatment is then performed by applying a constant potential difference of 8 V between two platinum spiral-wire electrodes (apparent surface area of 1 cm^2) for 2.5 h at room temperature (25 °C) (step-3). This alkaline-assisted electrochemical process promotes the formation of CDs with different surface functional groups. After electrolysis, the crude product is centrifuged at 6000 rpm for 10 min (step-4), and the supernatant is purified by dialysis against ultrapure water for 72 h using a membrane with a molecular weight cut-off of 0.1-0.5 kDa, with the water replaced every 24 h (step-5). Finally, the purified CDs are isolated by evaporating the water under reduced pressure (step-6). Among the electrochemical conditions investigated, applying a constant potential difference of 8 V to the aqueous precursor produced the highest CD yield compared with the other tested voltages and galvanostatic conditions. This approach provides a potential route for valorizing orange peel waste by converting its aqueous by-product into functional carbon nanomaterials.[35-38,7]

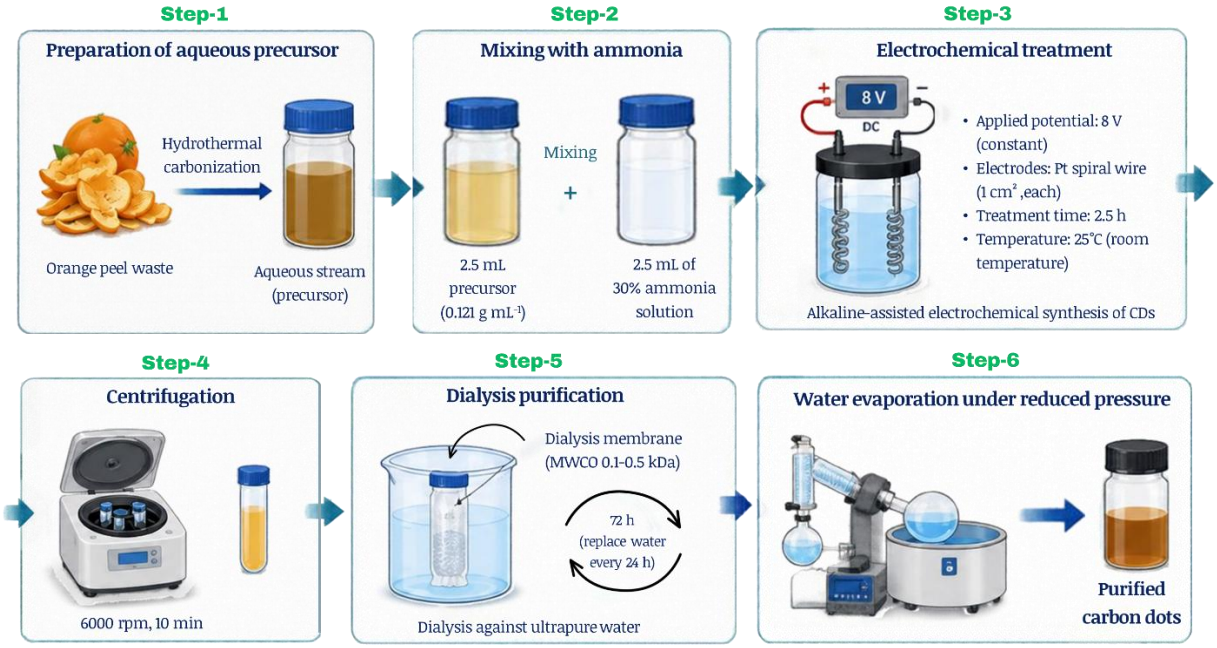


Figure 4. Electrochemical synthesis of OP-CDs from the aqueous by-product of hydrothermal carbonization including precursor preparation (step-1), mixing (step-2), electrolysis (step-3), centrifugation (step-4), dialysis (step-5), and purification (step-6).

III. Characterization of Orange Peel-Derived Carbon Dots

Orange peel-derived carbon dots are characterized using various techniques to evaluate their structural, chemical, morphological, and optical properties. These techniques provide information on particle size, morphology, carbon structure, surface functional groups, elemental composition, and optical properties. Such characterization helps explain the physicochemical properties of OP-CDs, particularly their antioxidant activity and UV-absorbing potential, which are relevant to their prospective application in anti-aging facial serum. Common techniques for characterizing OP-CDs include transmission electron microscopy (TEM) and high-resolution TEM (HRTEM) for analyzing particle morphology, size, and lattice structure; Raman spectroscopy for examining carbon structure and graphitic order; Fourier-transform infrared spectroscopy (FTIR) for identifying surface functional groups; X-ray photoelectron spectroscopy (XPS) for determining surface elemental composition and chemical states; UV-visible (UV-Vis) absorption spectroscopy for evaluating optical absorption, including UV absorption; and photoluminescence (PL) spectroscopy for assessing photoluminescence properties. Collectively, these techniques help to elucidate the physicochemical and optical properties of OP-CDs relevant to their potential application in anti-aging facial serum.

Morphological and Structural Characterization using TEM and HRTEM:

The morphology, particle size, and structural features of OP-CDs are commonly characterized using TEM and HRTEM. TEM provides information on particle size distribution and morphology, while HRTEM reveals lattice fringes that help identify ordered carbon domains. TEM analysis of CDs synthesized from orange peel revealed predominantly spherical particles ranging from 1.5 to 13.5 nm, with most particles measuring 3.5-5.5 nm. HRTEM further revealed a lattice spacing of 0.215 nm, suggesting the presence of an ordered carbon domain within the particles.[10] Similarly, spherical OP-CDs synthesized by hydrothermal carbonization at 180 °C exhibited particle sizes of approximately 2-7 nm.[33] In another study, orange peel-derived carbon quantum dots exhibited relatively uniform, spherical morphologies, with an average diameter of 4.58±1.37 nm and a size range of 2-8 nm.[37] These findings indicate that orange peel can serve as a suitable precursor for producing nanoscale carbon materials with different morphological and structural characteristics. Comparable nanoscale dimensions have also been reported for CDs derived from other biomass sources, with particle sizes ranging from approximately 3.5±0.6 to 6.0±0.8 nm.[6] However, the particle size of OP-CDs can vary depending on the precursor composition and synthesis conditions. For example, orange peel-derived carbon nanoparticles with sizes ranging from 50 to 105 nm have also been reported.[25] Such variations may arise from differences in synthesis methods, particle growth, and aggregation. Overall, TEM and HRTEM provide valuable insights into the morphology, particle size, and structural features of OP-CDs, complementing other analytical techniques used to characterize their physicochemical properties.

Optical Characterization using UV-Vis and PL Spectroscopy:

UV-Vis's absorption and PL spectroscopy are important techniques for characterizing the optical properties of OP-CDs. UV-Vis's spectroscopy provides information about their light-absorption characteristics, while PL spectroscopy reveals their fluorescence behavior.

UV-Vis Absorption Properties:

OP-CDs exhibit UV absorption primarily due to $\pi \rightarrow \pi^*$ transitions in conjugated sp^2 carbon domains and $n \rightarrow \pi^*$ transitions associated with surface functional groups, such as carbonyl groups. Hydrothermally synthesized OP-CDs showed an absorption band near 268 nm[33], while electrochemically synthesized CDs exhibited a band around 250 nm[7]. In addition, oxygen-containing CQDs exhibited broad absorption between 250 and 300 nm, with a shoulder near 312 nm.[23] These findings indicate the UV-absorbing potential of OP-CDs. However, absorption peaks alone do not establish effective protection across the entire UV-A and UV-B regions, and their performance in facial serum requires further evaluation.

Photoluminescence Properties:

The PL characteristics of OP-CDs vary with their synthesis methods and surface chemistry. CQDs synthesized using different precursors and methods exhibited emission peaks near 445 nm,[10] where 419 nm for hydrothermally synthesized OP-CQDs with a reported photoluminescence quantum yield (PLQY) of 21.7%.[37] Electrochemically synthesized CDs displayed emission near 438 nm, with a PLQY of approximately 2.2%.[7] Excitation-dependent emission has also been observed in CDs derived from orange and other vegetable peels.[24]

Overall, UV-Vis and PL spectroscopy provide complementary information on the optical properties of OP-CDs. UV-Vis's absorption is particularly relevant to exploring their potential use in UV-protective anti-aging facial

serum, while PL analysis helps characterize their fluorescence behavior. Further studies are needed to assess their UV-protective performance, formulation stability, and suitability for topical application.

Surface Functional Groups Characterized by FTIR:

FTIR spectroscopy is widely used to identify surface functional groups in carbon dots by analyzing their characteristic vibrational bands. OP-CDs exhibited bands at approximately 3371 cm^{-1} (O-H stretching), 2962 cm^{-1} (C-H stretching), 1768 cm^{-1} (C=O stretching), 1666 cm^{-1} (O-H bending), and 1593 cm^{-1} (aromatic C=C stretching).[33] Similarly, CQDs synthesized from orange peel showed bands at 3556 cm^{-1} (O–H), 3412 cm^{-1} (N–H), 2298 cm^{-1} (C≡N), 1640 cm^{-1} (C=O/C=N), and 1146 cm^{-1} (C–O).[10] Another study reported bands at 3434, 2919, 2850, 1635, 1096, and 806 cm^{-1} for orange peel-derived oxidized carbon quantum dots (O-CQDs).[23] CDs prepared from carrot, orange, and cucumber peels showed characteristic bands near 3407 cm^{-1} (O-H), 1620 cm^{-1} (aromatic C=C), and 610 cm^{-1} (C-O-C).[6] Other biomass-derived CDs have also demonstrated O-H/N-H, amide, ester, carbonyl, amine, and sulfur-containing functionalities.[3] Collectively, these findings demonstrate that biomass-derived CDs possess diverse surface functional groups, depending on the precursor and synthesis conditions. Hydroxyl and carboxyl groups, where present, may influence water compatibility and interactions with the surrounding environment. Some surface functionalities may also contribute to antioxidant-related activity, highlighting the potential of OP-CDs as functional ingredients for anti-aging facial serum. However, their specific contributions to antioxidant performance and suitability for topical formulations require further investigation.

Surface Elemental Composition and Chemical States by XPS:

XPS provides information about the elemental composition and chemical states of carbon dots. Unlike FTIR, which identifies functional groups through molecular vibrations, XPS distinguishes chemical environments based on the binding energies of core electrons. It is particularly useful for identifying surface functionalities and investigating the chemical states of elements in CDs.[39,40] XPS analysis of OP-CDs confirmed the presence of oxygen-containing surface groups. The high-resolution C 1s spectrum exhibited peaks at 284.9, 285.9, 287.3, and 288.8 eV, assigned to C-C/C=C, C-O/C-OH, C=O, and O-C=O environments, respectively. The O 1s spectrum showed peaks at approximately 530.5, 531.9, and 533.2 eV, corresponding to different oxygen-containing chemical environments.[33] These findings indicate the co-existence of carbon-rich domains and oxygen-containing surface functionalities. A recent study further demonstrated that the surface chemistry of OP-CDs can vary with the ripeness of the precursor, influencing the relative contributions of oxygen-and nitrogen-containing groups.[39] Moreover, XPS can identify the chemical states of nitrogen and sulfur in CDs through high-resolution N 1s and S 2p spectra, respectively. Such analyses provide insights into the bonding environments and surface composition of CDs, helping to clarify how surface functionalization influences their physicochemical and optical properties.[40]

IV. Antioxidant and UV Protective Properties of Carbon Dots

Antioxidant Activity:

Carbon dots can scavenge reactive radical species through hydrogen atom transfer (HAT) and electron transfer (ET) mechanisms. Surface hydroxyl, carboxyl, and amino groups may donate hydrogen atoms or electrons to reactive radicals, while the resulting surface radicals may be stabilized by the carbon-dot structure. In addition, electron-rich sp^2 carbon domains may facilitate electron transfer or radical adduct formation, contributing to radical stabilization (**Figure 5**). Experimental studies on surface-functionalized carbon nanodots have shown that carboxyl (-COOH) and amino ($-NH_2$) groups can contribute to DPPH radical scavenging through direct or indirect hydrogen atom transfer.[41-43] These mechanisms suggest that surface functional groups and conjugated carbon domains may collectively influence the radical-scavenging activity of OP-CDs and their potential to mitigate oxidative stress.[44-46]

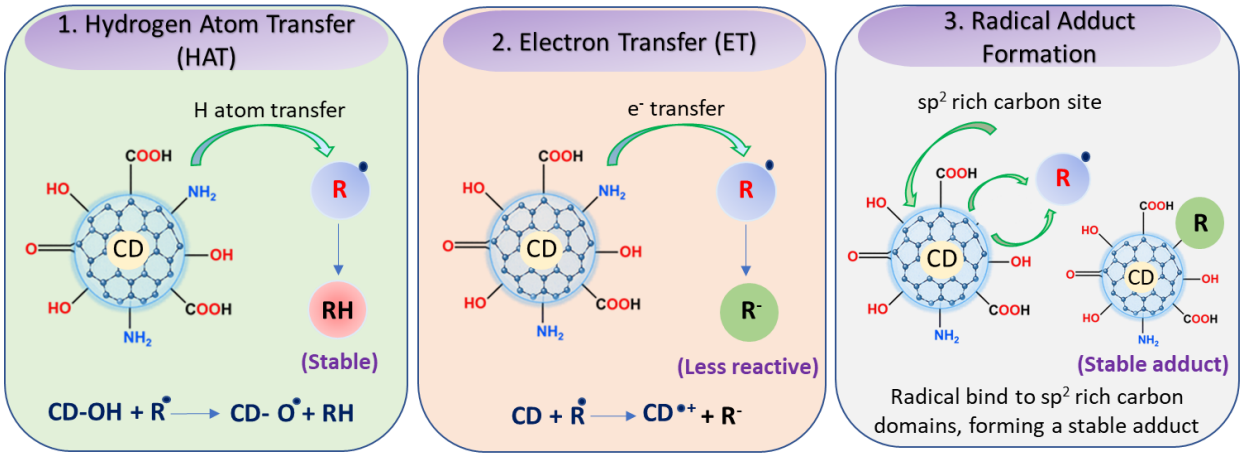


Figure 5. Radical-scavenging mechanisms of CDs including hydrogen atom transfer (HAT), electron transfer (ET), and radical adduct formation.

The antioxidant potential of CDs is commonly evaluated using the DPPH radical-scavenging assay. In this method, a DPPH solution is mixed with a CD dispersion and incubated in the dark before its absorbance is measured at 517 nm using a UV-Vis's spectrophotometer. The decrease in absorbance at this wavelength relative to the DPPH control indicates radical scavenging. Depending on the experimental protocol, the background absorbance of the CD dispersion may also be corrected using an appropriate sample blank.[47,48,6] The DPPH radical-scavenging rate can be calculated using the following equation, which accounts for the background absorbance of the CD dispersion:

DPPH radical-scavenging rate (%) = $[1 - (A_1 - A_2)/A_o] \times 100$

where A_1 is the absorbance of the CD-DPPH mixture, A_o is the absorbance of the DPPH control, and A_2 is the absorbance of the CD-water mixture, all measured at 517 nm. Subtracting A_2 corrects for the background absorbance of the CD dispersion.[48] Reported experimental results indicate that the DPPH radical-scavenging activity of OP-CDs can increase with increasing concentration, with values ranging from approximately 16% to 77% under the investigated conditions.[49,24] In another study, carbon dots synthesized from orange peel using a green hydrothermal method exhibited approximately 87% antioxidant efficiency, the highest among the carbon dots prepared from orange, carrot, and cucumber peels.[27] However, the measured activity may vary depending on CD concentration, surface functional groups, synthesis conditions, and assay protocols. These findings suggest that OP-CDs may have potential as antioxidant ingredients in anti-aging facial serum formulations. Their radical-scavenging properties may help protect the skin against oxidative damage associated with premature aging. Nevertheless, further studies are needed to establish their optimal concentration, antioxidant performance in finished serum formulations, long-term stability, and safety for topical application.

UV Protective Potential:

Carbon dots exhibit UV-absorbing properties due to their conjugated sp^2 carbon domains and surface functional groups. Their absorption spectra typically show strong absorption in the UV region (200-400 nm) with the absorption bands generally attributed to $\pi \rightarrow \pi^*$ transitions associated with C=C bonds and $n \rightarrow \pi^*$ transitions involving C=O or C≡N groups (**Figure 6**). The optical absorption behavior of CDs depends on the size of their conjugated domains, the nature of their surface functional groups, and the oxygen and nitrogen containing species present in their structures.[49-53] These structural features influence the interaction of CDs with UV radiation.

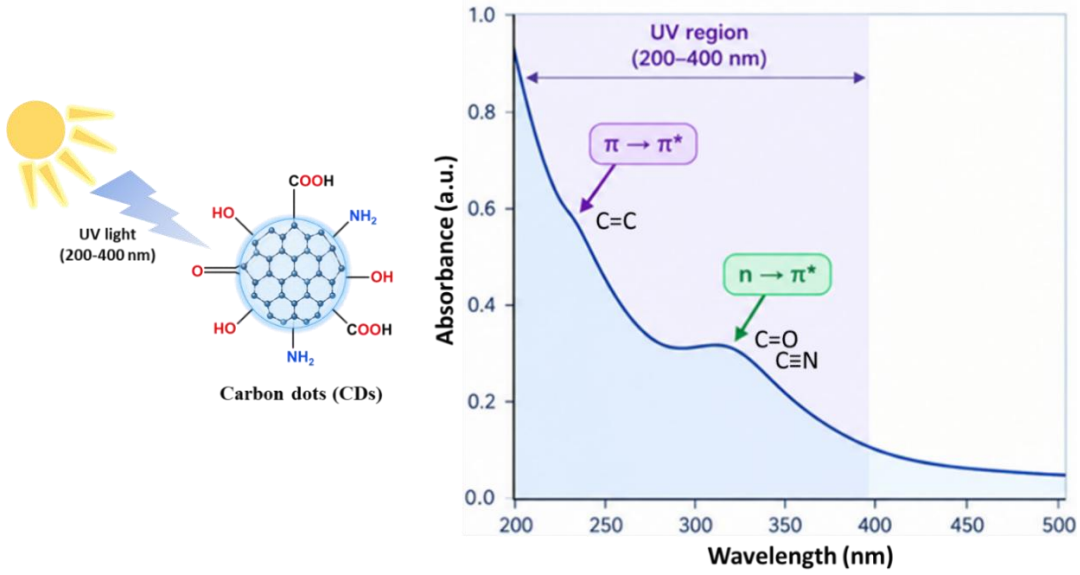


Figure 6. UV absorption properties of carbon dots arises from π→π* (C=C) and n→π* (C=O, C=N) transitions.

Ultraviolet radiation is commonly classified into UV-A (315-400 nm) and UV-B (280-315 nm). UV-A can penetrate into the dermis and contributes to skin photoaging, including wrinkles, pigmentation changes, and loss of elasticity, primarily through reactive oxygen species (ROS) generation and oxidative damage. In contrast, UV-B primarily affects the epidermis and can cause sunburn and direct DNA damage. Both UV-A and UV-B contribute to the risk of skin cancer.[54,55] Therefore, materials capable of attenuating both UV-A and UV-B radiation may be of interest for developing complementary UV-protective skincare formulations. OP-CDs have demonstrated promising broad-spectrum UV-absorbing properties. One study reported approximately 98% UV-A absorption (315-400 nm) and 100% UV-B absorption (280-315 nm) at a concentration of 1.7×10^{-2} mg/mL, while maintaining approximately 99% visible-light transmittance.[56] The high UV absorption, combined with minimal attenuation of visible light, highlights the potential of OP-CDs as optical materials for UV-shielding applications. Their ability to absorb UV radiation while allowing most visible light to pass through may also be advantageous for developing facial serum formulations with desirable optical properties. Furthermore, the reported stability of OP-CDs under different temperature and pH conditions supports further investigation of their suitability for skincare formulations.[57] These findings highlight the promising UV-absorbing properties of OP-CDs and support further investigation of their potential for UV-protective skincare applications. Further studies are therefore needed to evaluate their photostability, skin compatibility, formulation stability, and ability to mitigate UV-induced skin damage before their potential use in anti-aging serum can be established.[58,14] The UV-absorbing properties of OP-CDs, together with their potential antioxidant activity, suggest their promise as complementary functional ingredients in anti-aging serum formulations. UV-A and UV-B radiation contribute to oxidative stress and skin photoaging, highlighting the potential relevance of ingredients that combine UV absorption with antioxidant properties. Overall, the UV-absorbing and potential antioxidant properties of OP-CDs suggest their promise as complementary functional ingredients in anti-aging serum formulations. However, further studies are required to establish their safety, stability, and effectiveness in reducing UV-induced skin damage under practical skincare conditions.[24,44,45]

V. Incorporation of Carbon Dots into Anti-Aging Serum

Serum as a Delivery System:

Facial serums are concentrated skincare formulations designed to deliver active ingredients (**Figure 7**). The skin consists of two major layers: the epidermis, which forms the outer protective barrier, and the underlying dermis, which contains collagen, elastin, and blood vessels.[59,17] The epidermis helps protect the body against external threats and prevents excessive water loss.[17] The dermis is the thickest layer of the skin and contains collagen and elastin fibers that provide strength, structural support, and elasticity. UV radiation and oxidative stress can damage these components, contributing to wrinkles, reduced elasticity, and skin aging.[60] Depending on their

composition and formulation, facial serums may facilitate the topical delivery of selected active ingredients and support targeted skincare applications.[15] Their lightweight texture and generally non-greasy properties make them suitable for incorporating functional ingredients intended to address specific skin concerns.[16] These formulations may target skin aging, uneven skin tone, and dehydration. Certain formulations may also help improve the appearance of fine lines and wrinkles and reduce oxidative damage associated with free radicals.[17,18] However, these benefits depend on the ingredients, formulation characteristics, and demonstrated efficacy of the individual product.

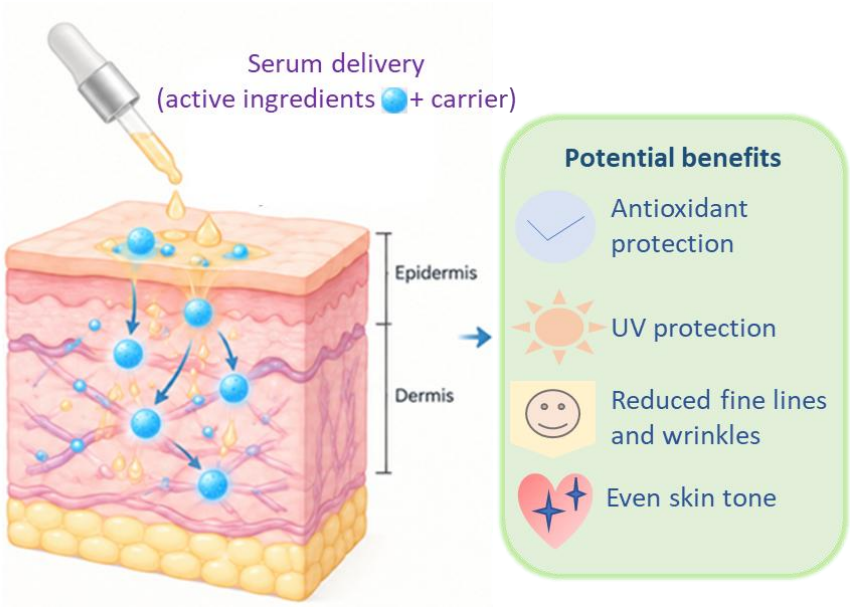


Figure 7. Serum as a delivery system for active ingredients.

These characteristics make facial serums a potentially suitable formulation platform for incorporating functional nanomaterials such as carbon dot. Their incorporation may provide a means of exploring the antioxidant and UV-protective properties of CDs in topical skincare applications. In particular, OP-CDs are of interest because orange peel contains organic constituents, including sugars, organic acids, flavonoids, and phenolic compounds. These constituents can act as carbon precursors and influence the formation, surface functional groups, and physicochemical properties of the resulting CDs. However, the composition and biological activity of OP-CDs depend on the synthesis and purification conditions, and their potential benefits in anti-aging facial serum require further investigation.[61,62,14]

Carbon Dots in Serum:

OP-CDs may be explored as functional ingredients in anti-aging facial serum because of their reported antioxidant and UV-absorbing properties. Similar antioxidant and UV-protective properties have been reported for biomass-derived carbon quantum dots in other material systems, highlighting their potential functional applications.[63] However, their practical incorporation into serum formulations requires careful optimization of concentration, compatibility with other ingredients, and physicochemical stability.[64] The concentration of OP-CDs should be optimized to achieve the desired functional activity while maintaining adequate dispersion and formulation stability.[14] Humectants, such as glycerin or hyaluronic acid, may be included to support skin hydration,[65,66] while an appropriate preservative system may be necessary to control microbial growth.[67,68] In addition, fluorescent carbon dots derived from carmine cochineal have demonstrated moisture-retention capability in moisturizing lipstick, suggesting that certain carbon dots may also have potential as moisturizing additives in topical formulations.[69] The compatibility of OP-CDs with these components and the stability of the resulting formulation should be evaluated under suitable storage conditions.[70-72]

Although previous studies have reported antioxidant and UV-related properties of different carbon dots, these findings do not establish the clinical anti-aging efficacy of OP-CD-containing facial serum. In one study, plant-

derived carbon dots were evaluated for biocompatibility using L929 mouse fibroblast cells. Cell viability remained relatively high at lower concentrations but decreased to approximately 80% at higher concentrations after 24 h of exposure.[73] These findings highlight the importance of evaluating concentration-dependent cellular responses when investigating carbon dots for topical applications. However, results obtained from a mouse fibroblast cell line cannot establish the safety of OP-CDs in human skin or finished facial serum formulations. Further studies are therefore needed to assess skin penetration, skin compatibility, long-term safety, formulation stability, and efficacy.[14] Systematic formulation studies, followed by appropriate biological and clinical evaluations, are necessary to establish the potential of OP-CDs as functional ingredients in anti-aging facial serum.

Formulation Consideration:

The formulation of anti-aging facial serum containing OP-CDs requires careful consideration of several factors to ensure adequate stability, safety, and functional performance.

Carbon Dot Concentration: The concentration of OP-CDs is an important consideration in serum formulation because their antioxidant and UV-absorbing activities may depend on the amount incorporated. At very low concentrations, OP-CDs may provide limited radical-scavenging and UV-absorbing effects, potentially reducing their intended functional benefits.[14,61] Therefore, an appropriate concentration should be established experimentally to achieve the desired activity while maintaining adequate dispersion and formulation stability. At higher concentrations, some carbon-dot systems may undergo aggregation and aggregation-caused quenching, which can alter their optical properties and reduce fluorescence intensity. However, these effects depend on the specific carbon-dot system and should not be assumed to occur in all OP-CD formulations. Therefore, the concentration of OP-CDs should be optimized to balance functional activity, dispersion, stability, and overall serum performance.[14]

pH Compatibility: The pH stability of OP-CDs should be evaluated under different conditions to assess their optical behavior and suitability for incorporation into anti-aging facial serum.[74,21] The skin surface is naturally mildly acidic; therefore, the pH of topical formulations should be selected with consideration of skin compatibility and the intended application.[75] OP-CDs have shown pH-responsive optical behavior, with their UV-Vis's absorption peak shifting from approximately 429 nm at pH 4 to 445 nm at pH 10.[21] This behavior may be associated with changes in the protonation and deprotonation of surface functional groups, such as -OH, -NH_2, and -COOH.[76] Similarly, pH-dependent optical changes have been reported for curcumin-derived carbon dots,[74] carbon quantum dots derived from *Actinidia deliciosa*,[77] and orange juice-derived carbon dots, whose photoluminescence intensity varied under different pH conditions.[78] pH may also influence the antioxidant activity of OP-CDs. Under acidic conditions, protonation of surface groups, such as the conversion of -COO^- to -COOH, may alter their interactions with reactive species and consequently affect their radical-scavenging activity. Under alkaline conditions, increased deprotonation and changes in surface charge may also modify these interactions.[57] The direction and magnitude of these effects depend on the properties of the specific carbon dots and require experimental verification. Therefore, an appropriate formulation pH should be selected to maintain skin compatibility while preserving the stability and functional properties of OP-CDs.

Cytotoxicity and Safety: The safety of OP-CDs is an important consideration for their incorporation into anti-aging facial serum. Preliminary studies on orange- and citrus-derived carbon nanomaterials have reported encouraging biocompatibility. Bitter-orange-derived carbon dots maintained high cell viability over a broad concentration range (10–1280 μg/mL), with lactate dehydrogenase release remaining below approximately 5%, while orange peel-derived carbon nanoparticles also showed limited cytotoxic effects.[79,14,25] However, these findings relate to specific materials and experimental conditions and cannot establish the safety of OP-CDs for human skin. The biological effects of carbon dots may vary with concentration, particle size, surface charge, surface functional groups, and exposure conditions.[80,81,14,61] Therefore, concentration-dependent cytotoxicity, skin irritation, sensitization, and potential oxidative effects should be evaluated using appropriate biological models before topical application is considered.[82,83] In addition, light intensity, wavelength, temperature, and pH may influence the photostability of carbon dots. Prolonged light exposure can cause photodegradation and may generate smaller degradation products or reactive species, depending on the material and exposure conditions.[84]

Therefore, the photostability and biological safety of OP-CDs should be evaluated under relevant storage and illumination conditions.[61] These investigations are necessary to establish a suitable concentration range and appropriate storage conditions for future facial serum formulations.

VI. Research Gap and Future Perspective

OP-CDs have shown promising antioxidant and UV-absorbing properties, but their use as functional ingredients in anti-aging facial serum remains insufficiently investigated. Systematic investigations on optimal concentration, skin compatibility, long-term safety,[14,61,80,81] and stability under various pH,[14,21,61,74] temperature, and light-exposure conditions are among the major research needs. Further studies are particularly needed to understand the potential formation of photodegradation products and their effects on skin cells.[36] Furthermore, the efficacy of OP-CD-containing facial serum formulations in reducing oxidative stress and UV-induced skin damage needs to be evaluated using appropriate skin-relevant models.[85] Although related carbon-dot systems have been evaluated for their cytotoxicity and biological effects,[79,82,83] their findings cannot directly establish the safety or efficacy of OP-CD-based facial serum. Therefore, future studies should concentrate on improving synthesis and formulation conditions, assessing concentration-dependent cytotoxicity and photostability, and confirming antioxidant and UV-protective efficacy in practical topical applications. By addressing these issues, it will be possible to ascertain whether OP-CDs may be created into functional ingredients for anti-aging skincare that are safe, efficient, and sustainable. The possible skin advantages of using OP-CD serum on a daily basis, albeit these advantages need more clinical and experimental confirmation **(Figure 8)**.



Figure 8. The potential skin benefits of regular OP-CD serum use.

VII. Conclusion

Orange peel-derived carbon dots are promising sustainable nanomaterials for potential application in anti-aging facial serum formulations. Their UV-absorbing and antioxidant properties, together with their tunable surface functionalities, provide a potential basis for their use as multifunctional skincare ingredients. Incorporating OP-CDs into facial serum may offer an innovative approach to exploring strategies for mitigating UV-induced skin damage and oxidative stress while valorizing orange peel waste as a renewable carbon precursor. However, further optimization of OP-CD concentration, pH compatibility, formulation stability, photostability, skin compatibility, and long-term safety is essential before their practical application can be established. Further studies using skin-relevant biological models and well-designed serum formulations are needed to evaluate their efficacy, safety, and suitability for topical use. Overall, OP-CDs represent a promising sustainable approach to anti-aging skincare, although their practical benefits remain to be validated through further experimental and clinical investigations.

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