

Plasma-Engineered Anthocyanin Interfaces for Enhanced Dye-Sensitized Solar Cell Performance: A Brief Review of Synthesis and Device Performance

(Antara Muka Antosianin Kejuruteraan Plasma untuk Prestasi Sel Suria yang Dipertingkatkan Peka Pewarna: Suatu Kajian Ringkas Sintesis dan Prestasi Peranti)

SITI ROKHMANILA^{1,2}, AHMAD NAZRI DAGANG^{1,*}, HASIAH SALLEH¹, WAN HAFIZA WAN HASSAN¹ & NIK AZIZ NIK ALI³

¹*Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia*

²*Electrical Engineering Department, Faculty of Engineering, Pamulang University, Pamulang, 15310, Tangerang, Indonesia*

³*Faculty of Fisheries and Food Science, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia*

Received: 21 December 2025/Accepted: 2 September 2026

*Corresponding author; email: nazri.dagang@umt.edu.my

ABSTRACT

Anthocyanins are among the most extensively studied natural sensitizers due to their abundant availability, environmental friendliness, and optoelectronic properties that support solar energy conversion. However, their use is still limited by low photostability, weak interaction with semiconductor surfaces, and limited electron injection efficiency, resulting in poor device performance and scalability. Plasma treatment has emerged as an effective and environmentally friendly approach to modifying the dye–semiconductor interface by enhancing surface energy and interfacial charge transfer. Nevertheless, our understanding of how plasma parameters affect anthocyanin stability and DSSC performance remains fragmented. This review systematically evaluates recent developments in the synthesis, modification, and application of plasma-engineered anthocyanin interfaces in DSSCs, highlighting achievements, device optimization strategies, and prospects for commercialization to support the development of sustainable photovoltaic technology.

Keywords: Anthocyanin; DSSC; natural photosensitizers; plasma treatment; photovoltaic

ABSTRAK

Antosianin merupakan antara pemeka foto semula jadi yang paling banyak dikaji kerana ketersediaannya yang melimpah, sifat mesra alam dan ciri optoelektronik yang menyokong penukaran tenaga suria. Walau bagaimanapun, penggunaannya masih terhad oleh fotokestabilan yang rendah, interaksi yang lemah dengan permukaan semikonduktor serta kecekapan suntikan elektron yang terhad, yang seterusnya menyebabkan prestasi dan kebolehskalaan peranti yang rendah. Rawatan plasma telah muncul sebagai pendekatan yang berkesan dan mesra alam untuk mengubah suai antara muka pewarna-semikonduktor melalui peningkatan tenaga permukaan dan pemindahan cas antara muka. Namun begitu, pemahaman mengenai pengaruh parameter plasma terhadap kestabilan antosianin dan prestasi DSSC masih belum menyeluruh. Tinjauan ini menilai secara sistematik perkembangan terkini dalam sintesis, pengubahsuaian dan aplikasi antara muka antosianin yang direka bentuk menggunakan plasma dalam DSSC dengan menyoroti prestasi, strategi pengoptimuman peranti, serta prospek pengkomersialannya bagi menyokong pembangunan teknologi fotovoltan mampan.

Kata kunci: Antosianin; DSSC; fotovoltan; pemeka foto semula jadi; rawatan plasma

INTRODUCTION

As global energy demand rises alongside the urgent need to curb greenhouse gas emissions, the pursuit of sustainable, accessible, and affordable energy sources has become a defining challenge of the 21st century. In line with the United Nations Sustainable Development Goal 7 (SDG7), which promotes universal access to clean energy, dye-sensitized solar cells (DSSCs) have

emerged as a viable next-generation photovoltaic technology due to their low-cost materials, ease of fabrication, and compatibility with flexible substrates (Huang, Wang & Markides 2021; Omar, Ali & Abd Rahim 2020). Among the sensitizing agents used in DSSCs, natural anthocyanin-based dyes derived from plant sources, roots or leaves offer a sustainable alternative (Pramananda, Hadyan Fityay & Misran 2021).

Dyes used in DSSCs can be broadly classified into two main categories: synthetic dyes and natural dyes. Synthetic dyes are generally metal-complex-based, particularly ruthenium (Ru) complexes, which were intensively developed and later refined into N719, enhancing spectral response in the red and infrared light regions (Nagao et al. 2022). Synthetic dyes, particularly ruthenium complexes such as N3, N719, and black dye, have demonstrated high photovoltaic performance due to their broad absorption spectrum, good stability, and high charge transfer efficiency (Ritu, Gupta & Negi 2025). Photovoltaic testing under indoor lighting showed a power conversion efficiency (PCE) of 25.65% for the synthetic dye N719 (Elawady et al. 2026). Although superior in efficiency and durability, metal-based synthetic dyes have several drawbacks, including high production costs, complex synthesis processes, dependence on precious metals with limited availability, and environmental unfriendliness. These conditions have spurred research into natural dyes extracted from various plant sources—such as flowers, fruits, roots, stems, and leaves—using simple extraction methods with solvents like methanol or ethanol as alternative sensitizers (Kabir et al. 2022). Commonly used natural pigments include chlorophyll, carotenoids, anthocyanins, and betalains. Natural dyes such as sappan wood (*Caesalpinia sappan* L.), which contains anthocyanin pigments, have been shown to have a competitive conversion efficiency of up to 2.60% (Waode Sukmawati et al. 2024).

Natural anthocyanin dyes, noted for their ease of extraction, cost-effectiveness, and environmental compatibility, present a promising alternative to synthetic ruthenium-based dyes, which are often expensive and less sustainable (Alves et al. 2026). However, the inherent stability and efficiency of anthocyanin-based DSSCs is an area of ongoing research, with challenges mainly revolving around long-term performance, power conversion efficiency, low chemical stability, poor anchoring to the TiO₂ surface, and suboptimal charge transfer efficiency (Amogne, Ayele & Tsigie 2020; Jevtovic et al. 2026). Such drawbacks have prompted the development of innovative interface engineering strategies, one of which is plasma surface treatment. Atmospheric pressure plasma jet (APPJ) treatments offer a solvent-free, tunable, and sustainable plasma technique for modifying semiconductor surfaces, enhancing dye adsorption, and improving interfacial interactions. Hoffman et al. (2022) reported that plasma-treated photoanodes significantly enhanced anthocyanin dye loading, resulting in improved short-circuit current and overall cell efficiency.

Scopus data show that publications on anthocyanins and plasma treatments in DSSC applications increased from 2014 to 2024, indicating rising interest in integrating natural dyes with advanced surface engineering (Wu et al. 2025). China leads the global research output

in this area, followed by India and South Korea (Bong et al. 2022; Udomkun et al. 2020). Many previous reviews have explored the individual components of DSSCs or the performance of natural dyes. However, few have explicitly addressed the intersection of plasma engineering and anthocyanin interfacial behavior (Xu et al. 2024).

This review aims to critically evaluate the synergy between plasma surface modification techniques and the utilization of anthocyanin dyes in DSSCs. The main objective was to consolidate the existing knowledge on synthesis strategies, surface activation mechanisms, interfacial modifications, and performance of the resulting devices. By integrating experimental findings and mechanistic insights, this review also identifies emerging opportunities and unresolved challenges.

ANTHOCYANIN DYES FOR DSSCs

MOLECULAR STRUCTURE OF ANTHOCYANINS

According to Fu et al. (2026), anthocyanins are a prominent class of natural pigments characterized by a 2-phenylbenzopyrylium skeleton, which can be further modified with hydroxyl or methoxyl groups on the B-ring, thereby influencing their spectral properties and stability. In Figure 1(a), the number of hydroxyl groups on the B ring, for example, correlates with a bluer color. while methylation moves the color towards red and increases stability by reducing susceptibility to oxidation. Glycosylation patterns, especially at the C3 position, further modulate the stability of flavylum cations and their interconversion pathways, thereby influencing photophysical properties relevant for charge transfer processes in DSSCs (Tan et al. 2022). Moreover, O- glycosylation, especially at the C3 position, has been shown to interfere with the acid-base properties of the chromophore, significantly affecting the distribution of colored and colorless forms in aqueous solution, and thus affecting the light absorption efficiency in dye-sensitized solar cells (DSSCs) (Mahajan et al. 2024).

In Figure 1(b) these compounds display different colors (red, blue and purple) depending on the accumulation and absorbance of chlorophyll complementary light, and the pH value significantly affects the stability and color of anthocyanins, with significant degradation occurring at high temperatures (Ikhsan et al. 2026). Basic flavylum cations undergo reversible structural transformations, including protonation, deprotonation, and hydration, which determine their color expression at varying pH conditions such that flavylum cations (red in acidic media) transform into carbinol and chalcone pseudobases (colorless), or quinone anhydrobioses (blue/purple in neutral to alkaline conditions) each of which has a different absorption maximum and quantum yield for their application in optoelectronic devices (Fu et al. 2026). Increasing pH above 3.0–4.0 leads to rapid transformation

of colored flavylum cations into colorless carbinol or chalcone forms, thus, significantly reducing the light harvesting efficiency (Piryaei, Shabani & Alipour 2026).

EXTRACTION, PURIFICATION, AND STABILIZATION STRATEGIES (pH CONTROL, co-PIGMENTATION, METAL COMPLEXATION)

According to Bitwell et al. (2023), conventional extraction methods often involve solvent-based approaches utilizing acidified water or ethanol-water mixtures to optimize anthocyanin yield and stability, given their higher stability in acidic environments. The next step is purification, such as adsorption chromatography or membrane filtration, which aims to remove impurities that may interfere with the performance of anthocyanins as sensitizers or cause unwanted side reactions in DSSCs (Ferreira et al. 2020).

Some of the extraction method and conditions used for anthocyanin dye solutions are listed in Table 1. The table shows that anthocyanin extraction strategies are greatly influenced by the choice of method, operational conditions, and type of solvent used. Comparative studies of various extraction methods on plant sources show that modern techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), high hydrostatic pressure assisted extraction (HHPAE), supercritical fluid extraction (SFE), deep eutectic solvent extraction (DES), and natural deep eutectic solvents (NADES), and pressurized liquid extraction (PLE) significantly increase the extraction efficiency of bioactive compounds compared to conventional methods (Alves et al. 2026). Conventional methods, such as maceration, are still widely used due to their simplicity, but they are time-consuming and relatively inefficient (Oancea 2021). In contrast, modern technology-based approaches can significantly accelerate the process at moderate temperatures, resulting in higher anthocyanin yields without substantial degradation. The use of high-concentration ethanol solvents and acidic conditions (pH 1–3) generally supports the optimization of extraction yields (Vinh, Hanh & Tra 2026).

TOTAL ANTHOCYANIN CONTENT (TAC)

Accurate determination of anthocyanin concentration can be achieved through pH differential method, spectrophotometric methods, which rely on the Beer-Lambert law, or more advanced techniques such as high-performance liquid chromatography, providing insights into the total content and individual anthocyanin profiles (Casasanta, Falcini & Garra 2022). The disadvantage of the differential pH method is that it provides limited information about specific anthocyanin profiles, which can significantly affect the spectral response and redox properties of dyes in DSSC applications; however, it has the advantage of providing a quick assessment of total anthocyanin content (Ngamwonglumlert et al. 2020; Urbstaite, Raudone & Janulis 2022). Chromatography technique, often combined with mass spectrometry (HPLC-MS/MS), and ultra-performance liquid chromatography-electrospray tandem mass spectrometry (UPLC-ESI/MS) analysis (Ali 2022). Chromatography techniques can provide a more detailed compositional analysis, enabling the separation and quantification of individual anthocyanin compounds in complex extracts, thus providing an accurate correlation between molecular structure and photovoltaic performance (Thomas et al. 2022).

The diverse structural variations of anthocyanins, including differences in hydroxylation, methylation, and glycosylation patterns, affect their light absorption characteristics and stability within the DSSC environment (Rodrigues 2024). However, excessive increases in dye concentration beyond the optimal point can lead to dye aggregation, adversely impacting power conversion efficiency by reducing light absorption and increasing charge recombination in the DSSC (Tiwari, Srivastav & Srivastava 2024). The synergistic effect of plasma treatment combined with optimized anthocyanin content can result in a more uniform and robust dye adsorption layer, reducing aggregation and enhancing charge transfer kinetics (Srivastava et al. 2025). Table 2 presents several types of plasma (atmospheric pressure plasma jet (APPJ), dielectric barrier discharge (DBD), cold plasma (CP), continuous cold plasma (CCP),

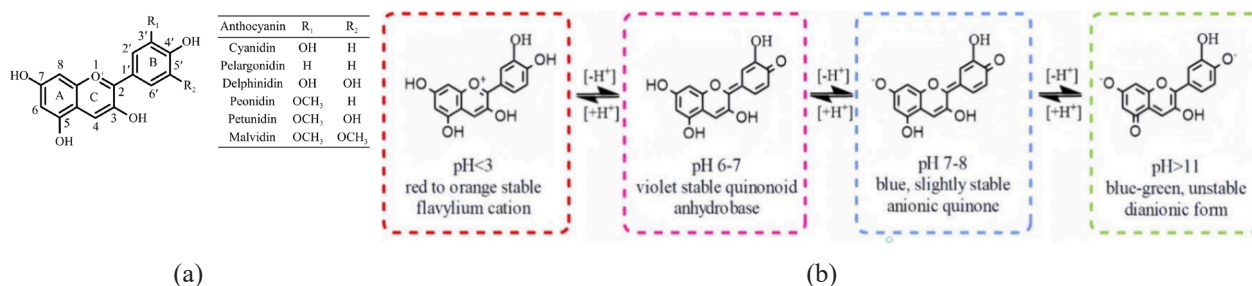


FIGURE 1. (a) Molecule structure of anthocyanin (Mattioli et al. 2020), and (b) Molecular states and electronic delocalization of cyanidin at different pH values (Wu et al. 2024)

TABLE 1. Extraction methods and conditions used for anthocyanin dye solutions

Method	Source	Condition	Main findings	References
UAE	Red rice bran (<i>Oryza sativa</i>)	78.37% ethanol, time 55 min, 3	TAC value 9.79 mg/100 g	(Wang et al. 2020)
UAE	Blueberry	70% ethanol, 40 °C, power 400 W, 40 min	TAC value (108.23 mg/100 g)	(Zhang et al. 2022)
UAE	<i>Vitis davidii</i> foex. pomace	70% ethanol, 313.15 K, time 10 min	TAC value (3.682 ± 0.051 mg/g)	(Zhang et al. 2024)
UAE	<i>Myrtus communis</i>	Solid-liquid (1:10), 25 °C, 40 kHz, 15 min	TAC 2.17 ± 0.05 mg/g	(Mértiri et al. 2025)
UAE	Mulberries	Ethanol, temperature 40 - 50 °C, time 6 h	TAC value (3.64 mg/g)	(Zhang et al. 2025)
UAE	Leumpua purple rice	40% propylene glycol, time 5 min	TAC value (4.41 ± 0.18 mg/g)	(Kongklai, Pomkham & Khat-udomkiri 2026)
MAE	Blueberry (<i>Vaccinium myrtillus</i> L.)	Methanol, Temperature (8-100 °C) and time (5-60 s)	Total monomeric anthocyanin (TMA) increased 40%	(Ferreira et al. 2020)
MAE	Blackberry, Cranberry	52% ethanol, 50 °C, time 4 min, power of 469 W	TAC value 2.18 0.06 mg/g)	(Ferreira et al. 2020)
MAE	<i>Brassica oleracea</i> L.	50% ethanol, time (5, 10, 15 min), power (200, 400 and 600 W), 40 - 70 °C	TAC value 220 mg/L in 10 min	(Yigit et al. 2022)
PLE	<i>Moringa oleifera</i>	Pressure of 1500-1650 psi, temperature 150 °C,	Total polyphenols (24.61 mg/g), total flavonoids (19.84 mg/g)	(Chatzimitakos et al. 2024)
PLE	Prickly pear (<i>Opuntia ficus-indica</i>)	50 °C, 1500 psi, pH 7	Total betalain yield 36.3%	(Višnjevec et al. 2024)
SCDE	Grape seeds	CO ₂ /H ₂ mixture (24:1 mol/mol), pressure (60–80 bar), time (5-9 min), 60 °C	Total phenolic content (TPC) 124.02 mg /100 mL	(Kavrut et al. 2026)
SEM	Chokeberry (<i>Aronia melanocarpa</i>)	Ethanol, temperature 46 °C, time 4.2 h	TAC value (0.34 mg/g)	(Wang et al. 2023)
HHPAE	<i>Euterpe edulis</i>	50 mL; 200 MPa; 5 min; 27 °C	TAC value 50 mg/100 mL	(de Oliveira et al. 2021)
SFE	<i>Myrtus communis</i>	45 °C, pressure of 23 MPa, time 2 h, CO ₂	TPC 11.59 ± 0.12 mg/g	(Mértiri et al. 2025)
DES	<i>Euterpe edulis</i>	Choline chloride: xylitol (5:1) + 30% water, time 2 min, 400W in 3 cycles	TAC value (1490.65 mg/100 g)	(Vannuchi, Braga & De Rosso 2022)
DES	Jaboticaba (<i>Plinia cauliflora</i>)	Choline chloride: malic acid (1:2) + 30% water, 10 MPa, 12 min, 90 °C, flow rate of 5.3 mL/min	TAC value (257.8 mg/100 g)	(Benvenuti, Zielinski & Ferreira 2022)
DES	Jaboticaba (<i>Plinia cauliflora</i>)	Choline chloride: lactic acid (1:2) + 35% water, 1500 psi, 12.5 min, 90 °C	TAC value (1468 mg/100 g)	(de Souza Mesquita et al. 2023)
NADES	Jussara (<i>Euterpe edulis</i>)	Choline chloride: xylitol (5:1) + 30% water, 2 min, 400W in 3 cycles	cyanidin-3-rutinoside (2318,48 µg/mL)	(Vannuchi et al. 2024)
NADES	Araza pulp (<i>Eugenia stipitata</i>)	pH ranged from 2.34 to 7.38, high density (1.234 to 1.375 g/mL)	TPC of 273.40 mg /g	(Sakurai et al. 2024)

TABLE 2. Plasma types used in total anthocyanin and their characteristics

Plasma type	Natural dye	Method	Condition	Main findings	References
APPJ	<i>Chenopodium formosanum</i>	differential pH	N ₂ , power (600-800 W), frequency (20-40 kHz)	TAC from 86.8 mg/g to 89.0 mg/g	(Lu et al. 2021)
DBD	Blueberries (<i>Vaccinium corymbosum</i>)	UPLC-ESI	Ar, time (90, 120, 150, 180 s), voltage (25, 30, 35 kV)	Increase in TAC (8 - 13%)	(Xu et al. 2024)
DBD	Clove (<i>Syzygium aromaticum</i>)	HPLC	N ₂ , time (5,10, and 15 min), flow rate (1 L/min), 15 kV, 345 Hz	TAC value 748.374 mg/g	(Alashti et al. 2024)
CP	cocoa powders	HPLC	N, H ₂ , O ₂ , time (20, 30, 40 min)	TAC decreased by 87% and 83% after heavy alkalization	(Palabiyik et al. 2023)
CP	<i>Lonicera japonica</i>	differential pH	Ar, power (100, 200, 300 W)	increased of TAC from 13.35 to 20.47%	(Li et al. 2023b)
CP	Butterfly pea (<i>Clitoria ternatea</i>)	UPLC-ESI	O ₂ , 80 kV, frequency (30-125 kHz), power 0.7 kW, gas flow rates (1, 5, 7 L/min), time (1, 3, 5 min)	Increased of TAC (+92% for 5 min at 180 V) and phenolic content (+32% for 3 min at 100 V)	(Jan & Gavahian 2024)
CP	Mangosteen (<i>Garcinia mangostana</i>)	differential pH	N ₂ , time (2-10 min), flow rate (1-5 L/min)	TAC, ranging from 15% to 67%	(Panklai et al. 2025)
CP	<i>Aronia melanocarpa</i>	UHPLC-PDA	O ₂ , frequency 13.56 MHz, power 100 W,	TAC 84 - 89%	(Yusufoğlu et al. 2026)
CCP	Apple juice	differential pH	Ar, 25 °C for 30 days	The contents of polyphenols (24.9%, 14.6%, and 1.3%)	(Wong et al. 2025)
CAP	Butterfly pea (<i>Clitoria ternatea</i>)	differential pH	Gas (O ₂ , N ₂ , Ar), time (4-8 min), 220 V, gas flow rate (1.5 L/min)	The highest TAC (22.43 ± 0.31 mg/L), whereas Ar-8 min	(Altaf & Intipunya 2026)
CAPP	sour cherry juice	HPLC	O ₂ , voltage (10, 15, 20 kV), frequency (10, 15, 20 kHz), gas flow rate (3, 5, 7 L/min)	TAC value from 279 mg/g and 359 mg/g after plasma	(Pathak et al. 2020)
CAPP	Blueberries,	differential pH	N ₂ , time (5, and 10 min), 7 °C	TAC value 107.42 ± 15.07 mg/100 gr	(Pathak et al. 2020)

cold atmospheric plasma (CAP), and cold atmospheric pressure plasma (CAPP)) used for anthocyanin treatment, along with their corresponding characteristics (Bhushan et al. 2023).

ENERGY LEVEL ALIGNMENT (HOMO–LUMO) WITH COMMON SEMICONDUCTOR OXIDES (TiO₂, ZnO, SnO₂)

The wide band gap and favorable conduction band edges facilitate efficient electron injection from the excited anthocyanin dye, while its nanomorph morphology provides a large surface area for dye adsorption, thereby maximizing light harvesting (Alashti et al. 2024). However, proper alignment between the highest occupied anthocyanin molecular orbital energy level and

the lowest unoccupied anthocyanin molecular orbital energy level with the valence band and conduction band of TiO₂, respectively, is crucial to optimize charge separation and minimize recombination losses. Easy synthesis methods for ZnO nanostructures, such as nanowires or nanobars, potentially offer better electron transport pathways compared to the more tortuous pathways in TiO₂ nanoparticle films, which could improve charge collection efficiency (Amini, Zakerhamidi & Khorram 2021). Tin dioxide (SnO₂), with its wider band gap and higher conduction band edge compared to TiO₂ and ZnO, offers different energy level alignment for anthocyanin-sensitized solar cells, potentially facilitating higher open-circuit voltages (Habis, Zaraket & Aillierie 2022).

Plasma-induced surface modification can reduce charge transfer resistance by increasing the number of active adsorption sites and reducing the effective distance between the electron donor centers in the dye and the electron acceptors on TiO_2 (Arkhangelskiy et al. 2021). Plasma is also capable of shifting the energy levels at the interface through the formation of surface defects and interfacial dipoles (Bosco et al. 2026). The presence of these defects increases the concentration of charge carriers and shifts the Fermi level and conduction band toward more negative energies, thereby increasing the driving force for electron injection from the dye's LUMO level into the TiO_2 conduction band (Srivastava et al. 2025). Plasma-induced charge redistribution can generate a local dipole at the dye-semiconductor interface, causing a shift in the local vacuum level; this shift results in better energy level alignment between the dye's LUMO and the TiO_2 conduction band, thereby reducing the thermodynamic barrier to electron transfer (Kang et al. 2021).

PHOTODEGRADATION PATHWAYS AND MITIGATION STRATEGIES PRE-/POST-PLASMA TREATMENT

According to Moriones et al. (2025), the degradation mechanism usually involves irreversible cleavage of the chromophore, leading to color loss and reduced charge injection efficiency into the semiconductor, thus, reducing the power conversion efficiency of the cell. Photodegradation often occurs through photo-oxidation, which involves the formation of reactive oxygen species that attack the flavylum cation structure, leading to the formation of chalcones, which lack the chromophore properties essential for efficient light harvesting. The presence of ions and metals in the pH of the dye solution significantly affects the stability of anthocyanins, as these factors can stabilize flavylum cations through complexation or accelerate degradation through alternative reaction pathways (Diallo et al. 2023). In contrast, the phenomenon of co-pigmentation, in which anthocyanins associate with flavonoids or other organic molecules, can enhance their photostability by forming stronger complexes and thereby becoming less susceptible to photodegradation (Taveepanich et al. 2024). Plasma treatment can generate radicals that interact with anthocyanin molecules, potentially leading to the formation of more stable chromophores or surface-bound species that exhibit increased resistance to UV degradation (Ali, Attia & Rashed 2024). This approach can also lead to the formation of a cross-linked polymer layer that encapsulates the dye, thus, significantly increasing its photostability by limiting molecular mobility and exposure to external degradation. In addition, plasma can be used to pre-treat the anthocyanin dye itself, potentially improving its light absorption characteristics

or modifying its molecular structure to increase stability against photodegradation (Sebak et al. 2025).

Research conducted by Khosravi et al. (2024) shows that the photocatalytic performance of untreated ZnS/TiO_2 nanocomposites and ZnS/TiO_2 nanocomposites treated with plasma has been evaluated by measuring the decomposition of acid blue 113 dye solution (AB113) dye solution as a model reaction under UV irradiation at pH 7 after 25 min of UV irradiation, the AB113 dye was almost completely decomposed in the presence of ZnS/TiO_2 nanocomposites treated with nitrogen (N_2) plasma at around 95%. In contrast, the decomposition reached 64% and 46%, respectively, in the presence of ZnS/TiO_2 treated with tetrafluoromethane (CF_4) plasma gas and untreated ZnS/TiO_2 . When UV light shines, it produces the photons needed to create electron-hole pairs. The holes generated during plasma treatment can cause the band gap of the plasma-treated photocatalytic catalyst to narrow. In this case, electrons from the conduction band (CB) of ZnS move to the CB of TiO_2 , while hole transmission occurs from the valence band (VB) of TiO_2 to the VB of ZnS . This band structure facilitates the separation of electron-hole pairs, allowing electrons to reduce molecular oxygen and produce superoxide anion radicals (O_2^-), while holes oxidize H_2O to form hydroxyl radicals (OH).

PLASMA TECHNOLOGIES FOR DSSC INTERFACES

PLASMA TECHNOLOGIES

Plasma, generally defined as an ionized gas, consists of a complex mixture of charged and neutral species, including electrons, positive and negative ions, radicals, atoms, and molecules within this complex medium, electron temperatures typically range from 1 to 10 eV, with electron densities ranging from 10^9 to 10^{12} cm^{-3} , and degrees of ionization varying significantly from 10^{-6} to as high as 0.3 (Mostafa et al. 2025). Plasma treatment is very effective in changing the surface wettability of materials, converting hydrophobic surfaces to hydrophilic, or vice versa, by introducing polar functional groups or modifying the surface topography (Reza et al. 2024). The introduction of hydrophilic functional groups to the surface of the photoanode through plasma treatment can also improve the wetting characteristics and facilitate more uniform and denser adsorption of anthocyanin dye, thereby enhancing light absorption (de Moura et al. 2024). In addition to surface energy, plasma treatment can also modify the electronic properties of the semiconductor, potentially shifting the conduction band edge closer to the lowest unfilled molecular orbital of the sensitizer, thereby increasing the electron injection efficiency (Yusufoglu et al. 2026). Table 3 shows the types of plasma used and their characteristics in DSSC applications.

Cold Plasma

The low-temperature nature of cold plasma enables precise surface functionalization without compromising the overall material properties, a crucial aspect for maintaining the intrinsic performance characteristics of DSSC components (Li et al. 2023a). Cold plasma, characterized by a non-equilibrium state in which the electron temperature far exceeds the temperature of the main gas, is well suited for modifying heat-sensitive

materials such as anthocyanins due to its ability to induce significant chemical changes at or near room temperature (Amorim et al. 2023). The advantage of cold plasma is its ability to perform localized surface modification, which enables the formation of self-assembled monomolecular layers and special textures that can significantly affect charge transport dynamics and light absorption efficiency in solar cells (Li et al. 2023a).

TABLE 3. Plasma types used in DSSCs and their characteristics

Plasma type	Common gases	DSSC component	Treatment time	PCE (%)	References
APPJ	Ar	ITO/ PEI substrate/ TiO ₂ / N3 dye/ Pt	60 s	2.25%	(Wante, Aidan & Ezike 2021)
APPJ	O ₂	ITO/ TiO ₂ / N719 dye /Pt	(0, 1, 2, 3, and 4 min	9.12%	(Mostafa et al. 2025)
APP	N ₂	ITO/ TiO ₂ / N719/ Pt _x Fe _{1-x}	-	10.13%	(Cao et al. 2021)
APP	Ar	FTO/ Cu/CuO/ TiO ₂ / Blueberry dye/ Pt	2 min	0.20%	(Tao et al. 2025)
APP	Ar	FTO/ CuO/ TiO ₂ / Blueberry dye/ Pt	2 min	0.18%	(Tao et al. 2025)
DBD	N ₂	FTO/ SnO ₂ / Eosin Y dye / Pt/ FTO	10 min	1.53%	(Weerasinghe et al. 2021)
DBD	Ar	FTO/ SnO ₂ / electrolyte/ Pt/ FTO	10 min	1.16%	(Weerasinghe et al. 2021)
DBD	N ₂ , O ₂	FTO/ TiO ₂ / N719 dye	15 min	3.9%	(Nagao et al. 2022)
DBD	N ₂	(PEI-ITO)/ TiO ₂ / N3 dye	60 s	5.7%	(Wante, Aidan & Ling 2024)
RF	O ₂ , Ar	ITO/ ZnO/ PET/ D102 dye	-	5.68%	(Poonthong et al. 2024)
RF	Ar	FTO/ GO/ PAni@ZnO/ TiO ₂ / electrolyte/ Ag	0, 1, 2, 3, 4 and 5 min	5.33%	(Alresheedi et al. 2025)
RF	H ₂ , N ₂ , CH ₄ , O ₂	FTO/ TiO ₂ / N719 dye/Pt	50 min	5% - 11%	(Kim et al. 2026)
RF	O ₂	FTO /TiO ₂ / mM Y123 dye/ Cu	10 min	9%	(Santos, Ivanou & Mendes 2026)
PECVD	O ₂	FTO/ TiO ₂ / RrGO/ electrolyte	0, 2, 4, 6, 8, 10 min	6.31%	(Shahat et al. 2024)
PECVD	O ₂	FTO/Al ₂ O ₃ /TiO ₂ /electrolyte / Ag	0, 2, 4, 6, and 8 min	7.6%	(Sebak et al. 2025)
PECVD	N ₂	FTO/TiO ₂ / N719 dye/ Chitosan@PVA@Copper (II) Sulfate /FTO	0, 3, 6, 9, and 12 min	8.01%	(Almutairi, Aladim & Abdelhamid Shahat 2026)
PECVD	H ₂	ITO/ZnO/CNTs/ N719 dye/Pt	-	0.612%	(Alshahrie et al. 2022)
PECVD	H ₂	ITO/ZnO/RGO/ N719 dye/Pt	-	0.574%	(Alshahrie et al. 2022)
Oxygen plasma	O ₂	FTO/SnO ₂ / MAPbI ₃ / Spiro-OMeTAD/Ag	-	2.3% - 15.30%	(Muthukrishnan et al. 2022)
Oxygen plasma	O ₂	TiO ₂ /Ado dye/ Gr+Ag	1 min	5.27% - 7.52%	(Li et al. 2023)

A schematic diagram of the cold plasma (non-thermal plasma) system is shown in Figure 2. Gases from cylinders such as argon (Ar), helium (He), oxygen (O₂), or nitrogen (N₂) are fed into the plasma system through a regulator and flow controller to regulate the pressure and flow rate of the gas. An aerometer is used to monitor the gas flow rate to ensure proper plasma operating conditions. The pressure system, consisting of a vacuum pump, pressure gauge, and pressure controller, is used to regulate and monitor the pressure within the system according to the required operating conditions. The regulated gas then enters the cold plasma discharge chamber. In this section, a high-voltage power supply delivers a high electrical voltage to the high-voltage electrode. When a high voltage is applied between the high-voltage electrode and the ground electrode, a strong electric field is formed within the discharge chamber. The ground electrode and grounding system serve as an electrical reference path while also helping to maintain system stability and safety during the plasma generation process. Next, the resulting plasma or active species is directed toward the treatment chamber, where the sample or substrate is placed (Bertin et al. 2024).

Atmospheric Pressure Plasma Jets (APPJ)

Atmospheric Pressure Plasma Jets are operated at atmospheric pressure without the use of vacuum pumps and chambers that are expensive and require regular maintenance (Lee et al. 2022). This plasma technique allows precise manipulation of surface energy, wettability, and chemical functionalization, thereby improving dye adsorption and charge transfer kinetics and enabling surface modification of heat-sensitive materials, such as anthocyanins, without inducing thermal degradation in the solar cell architecture (Miao et al. 2025). Careful control over operational parameters gas composition facilitates the creation of surface defects, deposition of thin films (Hoffmann et al. 2022). Figure 3 illustrates the atmospheric-pressure plasma jet (APPJ) system used for plasma treatment of natural dye solutions. This setup consists of a gas supply unit, a flow meter, a high-voltage power supply, a quartz capillary tube, a powered electrode, a grounded electrode, and a liquid sample containing the dye, which is placed beneath the plasma jet. Upon application of high voltage, the working gas is ionized, producing a non-thermal plasma cloud at atmospheric pressure (Rebohle et al. 2022). Reactive plasma species then interact with the dye solution, inducing physicochemical modifications that can enhance dye adsorption onto TiO₂, improve charge transfer characteristics, and contribute to higher DSSC performance (Luu et al. 2025).

Dielectric Barrier Discharge (DBD)

Dielectric Barrier Discharge plasma sources are characterized by the presence of at least one insulating

layer between the electrodes, effectively limiting charge transport and enabling stable and uniform plasma generation at atmospheric pressure. This dielectric layer prevents arcing and allows the formation of non-thermal plasmas, which is crucial for treating fine organic molecules such as anthocyanins without thermal degradation (Avino et al. 2023). The main parameters affecting the characteristics of DBD plasmas are voltage, frequency, gas composition selection, and gap distance, each of which affects the plasma's reactive species composition and energy distribution (Astanehi et al. 2022; Russo et al. 2020). The gap distance between electrodes in a DBD reactor can affect the electric field distribution, plasma homogeneity, and diffusion path of reactive species to the material surface (Ji et al. 2026).

Figure 4 shows a schematic of the DBD plasma system used to generate plasma in the gap between two electrodes. The DBD system consists of a powered electrode, a dielectric barrier, a discharge gap, and a grounded electrode. AC power is supplied to the powered electrode through a high-voltage resistor. When high voltage is applied, an electric field forms in the discharge gap, causing the gas between the electrodes to ionize and produce a plasma discharge. A current probe is used to monitor the electric current flowing through the system while also limiting the current to prevent it from becoming excessive. The voltage and current signals obtained from the system are then transmitted to an oscilloscope, which displays the electrical waveforms so that discharge characteristics such as changes in voltage and current during the plasma process can be observed and analyzed (Wante, Aidan & Ling 2024).

Radio Frequency (RF) Plasma

Radio Frequency plasma is a type of non-thermal plasma technology generated by applying an alternating electric field at radio frequencies, typically 13.56 MHz (Karthik, Chand & Thomas 2023). The main advantage of RF plasma is its ability to produce various reactive oxygen species (ROS) and reactive nitrogen species (RNS), such as O, O₃, OH, NO, and NO₂ (Prime 2022). Based on system configuration, RF plasma is generally classified into capacitively coupled plasma (CCP) and inductively coupled plasma (ICP). In a CCP system, plasma is generated between two electrodes to which an RF voltage is applied, creating an electric field that accelerates electrons and sustains the ionization process (Mandracci 2024). In ICP systems, the electromagnetic field generated by an induction coil is used to transfer energy to the plasma. Inductively coupled plasmas are characterized by very high plasma densities and low electron temperatures, making them ideal for processes requiring precise control over ion flux and minimal thermal damage, such as uniform modification of anthocyanin layers or thin layer deposition for DSSCs (Mohammadi et al. 2024; Settapramote et al. 2021).

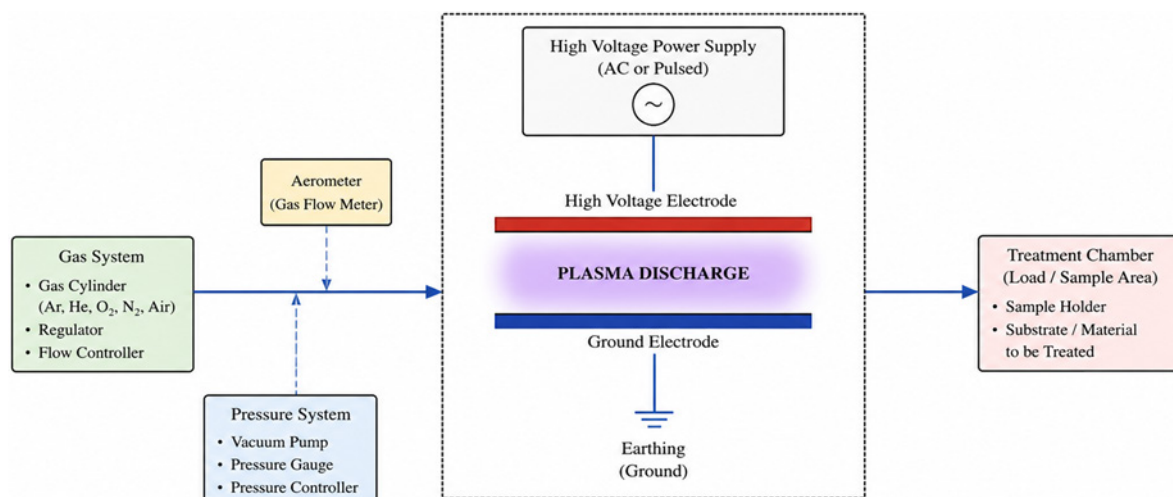


FIGURE 2. Schematic diagram of the cold plasma system

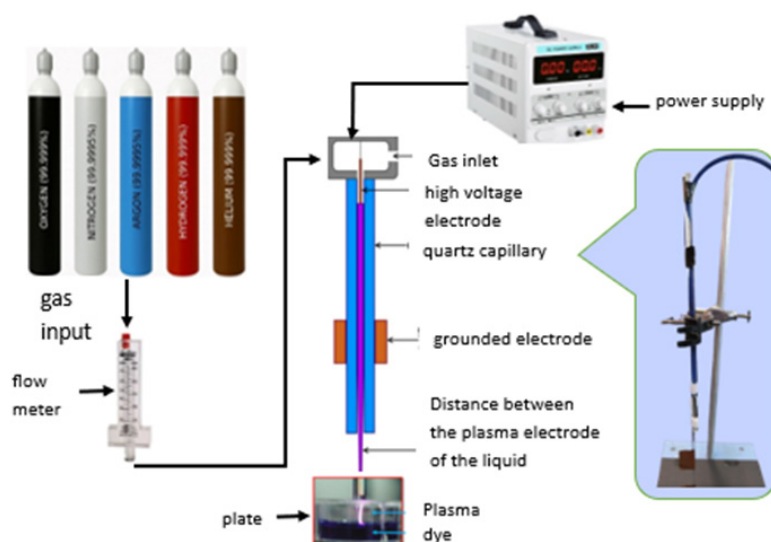


FIGURE 3. Schematic diagram of the APPJ system

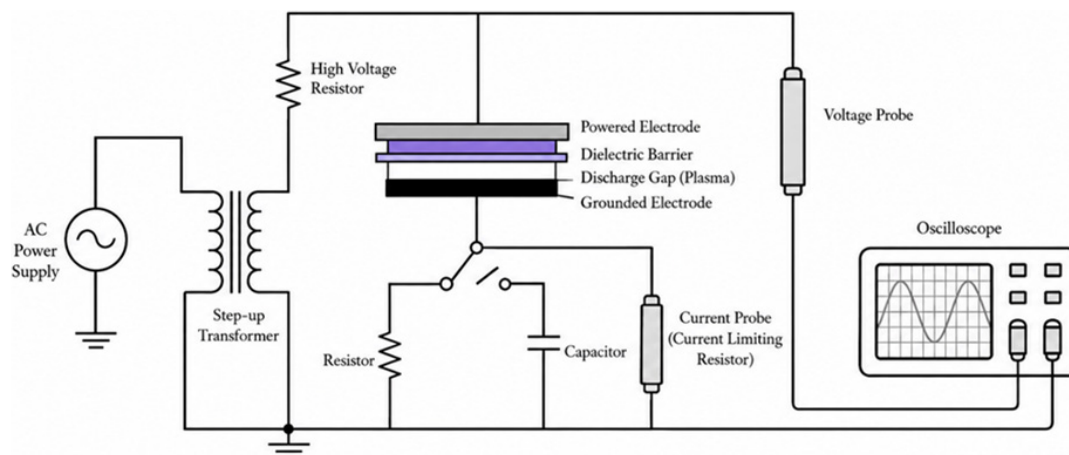


FIGURE 4. Schematic diagram of the DBD system

Additionally, RF plasma is also used in plasma-enhanced chemical vapor deposition (PECVD) processes to produce thin films with precisely controllable thickness and composition (Rahman Khan, Asrafali & Periyasamy 2024). This capability is crucial in the development of next-generation optoelectronic and photovoltaic devices. In plasma-enhanced chemical vapor deposition (PECVD), the type of plasma used is cold plasma, also known as non-equilibrium plasma (Shahat et al. 2024).

Inductively coupled plasma (ICP), is shown in Figure 5. Process gases, such as O_2 and sulfur hexafluoride (SF_6), are fed through the gas inlet into the plasma chamber, and the gas flow is controlled using a valve so that the flow rate and composition of the gas can be adjusted according to process conditions. Surrounding the outer part of the plasma chamber are inductive coils, which are connected to an RF coil to generate a high-frequency electric current. When the RF current flows through the inductive coils, it creates a time-varying electromagnetic field inside the plasma chamber. The resulting plasma is located above the substrate, which is mounted on a chuck (powered electrode). An RF platen connected to the chuck applies a bias to the substrate, allowing the energy of the ions striking the substrate's surface to be controlled. Helium (He) cooling gas is circulated through the underside of the chuck to help regulate the substrate's temperature during the plasma process (Lo et al. 2024).

GAS CHEMISTRY AND PLASMA-GENERATED REACTIVE SPECIES

The specific gas chemistry ($O^\bullet$, $N^\bullet$, $OH^\bullet$) in plasma treatment is crucial, as it dictates the type and concentration of reactive species generated, which in turn

govern the extent and nature of surface modification on materials such as anthocyanin-sensitized photoanodes (Kim et al. 2026). Oxygen radicals ($O^\bullet$), ozone (O_3), and atomic oxygen (O) are strong oxidants produced in oxygen-rich plasma environments, which effectively create polar functional groups such as hydroxyl ($-OH$), carbonyl ($C=O$), and carboxyl ($-COOH$) groups at the anthocyanin interface, thereby increasing surface hydrophilicity and promoting stronger intermolecular interactions, which are crucial for dye adsorption and charge transfer in DSSCs (Mostafa et al. 2025).

Plasma containing nitrogen ($N^\bullet$) adds amine, imine, and nitrile functions to the surface, which are crucial in modifying electronic properties and creating specific binding sites for anthocyanin molecules, thereby increasing the stability and efficiency of DSSCs. This nitrogen function can act as a Lewis base, forming coordination bonds with the semiconductor surface and potentially increasing the energy alignment between the dye and TiO_2 , resulting in more efficient electron injection (Khosravi et al. 2024). The presence of these nitrogen-rich functional groups can significantly influence the adsorption kinetics and molecular configuration of anthocyanins, potentially resulting in a more ordered and denser dye layer that enhances light harvesting and reduces aggregation-induced quenching (Guo et al. 2022). The formation of highly reactive hydroxyl radicals ($OH^\bullet$) through Fenton's reagent or other plasma-based methods facilitates surface functionalization, which is crucial for improving the adhesion and electrochemical activity of anthocyanin dyes (de Moura et al. 2024). In addition, the presence of hydroxyl groups can significantly increase the hydrophilicity of the interface, ensuring better electrolyte infiltration and facilitating efficient charge transport (Dudek et al. 2022).

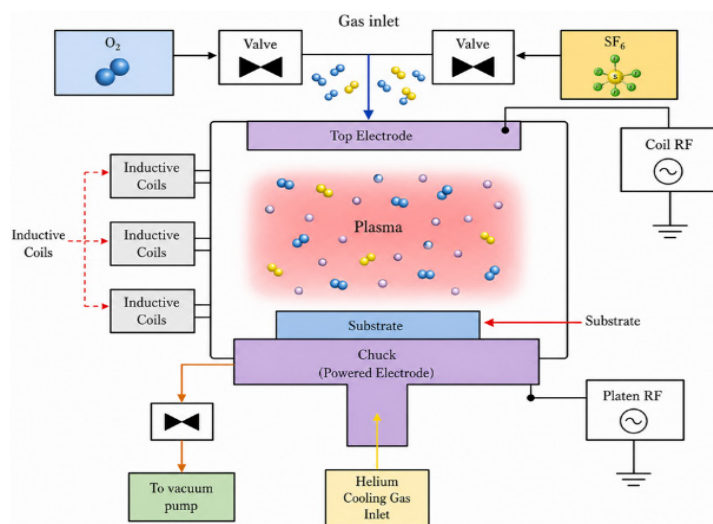


FIGURE 5. Schematic diagram of the ICP system

SURFACE MODIFICATION AND INTERFACIAL PHENOMENA INDUCED BY PLASMA

According to Ullah et al. (2021), surface modifications that fundamentally alter properties such as wettability, surface energy, and defect density are highly beneficial for natural dyes such as anthocyanins, which can exhibit varying binding affinities to different semiconductor substrates, thus, requiring proper interface engineering to maximize their photon harvesting capability and stability. Precise control over reactive species and energy flux in non-thermal plasma enables selective etching, deposition, or functionalization of surfaces, thereby determining parameters such as surface roughness, porosity, and the presence of specific functional groups that are important for dye adsorption and charge transfer kinetics (Mohammadi, Ishak & Sultan 2024). Plasma-induced surface modification can create structures such as nano grass that increase the surface area for dye adsorption and enhance light absorption, thereby contributing to higher short-circuit current density (Bertin et al. 2024). These structural and chemical modifications directly impact the efficiency of electron injection from excited anthocyanin dyes into the semiconductor, the rate of electron transport through the photoanode, and the charge recombination dynamics at various interfaces within the DSSC (Amogne, Ayele & Tsigie 2020; Thakur et al. 2022).

Defect Passivation

Plasma treatment offers an effective strategy for defect passivation by saturating these active sites with reactive species, thereby reducing charge traps and increasing charge carrier lifetime and collection efficiency (Barek 2021). This process involves the removal of defects in the bulk semiconductor and on its surface and interface, which otherwise act as recombination centers that reduce open-circuit voltage and fill factor in solar cells (Hoffmann et al. 2022). This passivation minimizes charge carrier losses and promotes efficient electron injection from the dye to the semiconductor, which is crucial for achieving high power conversion efficiency in DSSCs. Strategic incorporation of passivators at the interface, such as that achieved through plasma treatment, can significantly reduce defect density and enhance charge carrier recombination dynamics and charge extraction efficiency (Liu et al. 2022).

Surface Energy Tuning

Precise control of surface energy is essential for optimizing the spread and adhesion of subsequent layers, such as dye solutions and electrolytes, ensuring uniform film formation and intimate interface contact (Shahat et al. 2024). By adjusting surface energy, plasma treatment can optimize interface properties, thereby improving the overall performance and stability of DSSCs (Thakker, Sun & Bucknall 2022). This fine-tuning of

surface energy also plays a vital role in reducing issues such as void formation and high interface resistance, ensuring more intimate contact between electrode components and electrolytes (Roman et al. 2024). This leads to a more homogeneous distribution of redox mediators and improved ion transport within the device, both of which are important for sustainable performance (Avino et al. 2023).

ENVIRONMENTAL IMPACT ASSESSMENT

The environmental impact of plasma processes extends beyond energy consumption to include by-product production, waste disposal, and depletion of rare or toxic materials (Spadaro et al. 2023). Such assessments should critically compare the environmental performance of plasma-processed DSSCs with other photovoltaic technologies, taking into account factors such as embodied energy, greenhouse gas emissions, and resource depletion (Błaszczuk et al. 2021). Addressing these challenges requires sophisticated modelling and simulation tools to predict plasma behavior on a larger scale, alongside iterative experimental validation to refine process parameters to be industrially relevant (Cellura et al. 2024). Environmental impact assessment is also crucial, ensuring that the benefits of plasma-enhanced DSSC outweigh the potential ecological drawbacks associated with the manufacturing process (Yang et al. 2021).

SYNTHESIS AND FABRICATION WORKFLOWS INVOLVING PLASMA

BASELINE DSSC FABRICATION

Boldrini et al. (2023) state that dye-sensitized solar cells are photoelectrochemical devices that convert solar energy into electrical energy, typically consisting of a photoanode, dye sensitized, counter electrode, and electrolyte containing redox mediators such as iodide/triiodide. Furthermore, the sensitized, often using a natural dye such as anthocyanin, is adsorbed onto the surface of the semiconductor, forming a single layer that absorbs incoming photons and injects electrons into the conduction band of the oxide (Tiwari, Srivastav & Srivastava 2024). This electron injection initiates the photovoltaic process, with the dye then being regenerated by redox pairs present in the electrolyte, which are subsequently reduced at the counter electrode (Thakker, Sun & Bucknall 2022). Plasma can be utilized to create cross-linked polymer networks within gel electrolytes, improving their mechanical stability and preventing leakage while maintaining adequate ionic mobility (Coad et al. 2022). Furthermore, plasma-assisted polymerization or deposition techniques can be used to form a thin conformal passivation layer within the electrolyte, which

effectively reduces charge recombination at the photoanode/electrolyte interface and further improves charge collection efficiency (Mostafa et al. 2025).

PLASMA MODIFICATION OF ELECTROLYTES/GEL MATRICES

Modification of the electrolyte plasma and gel matrix is a crucial strategy for improving the performance and stability of DSSCs, particularly by increasing ionic conductivity, reducing solvent evaporation, and mitigating corrosive interactions with other device components (Coad et al. 2022). Such modifications can lead to the development of quasi-solid electrolytes or solid-state electrolytes with superior long-term stability and reduced leakage issues, thereby addressing key challenges in DSSC commercialization (Wong et al. 2025). Furthermore, plasma can be utilized to create a more stable and intimate interface contact between the electrolyte and the electrode, thereby reducing interface impedance and improving overall device stability (Pan et al. 2026). This interface, which acts as a crucial barrier, can effectively prevent direct contact between the electrolyte and the active electrode material, thereby suppressing unwanted parasitic reactions and maintaining stable electrochemical cycles (Wu et al. 2025). Such an interface can also facilitate faster ion transport by providing a clearer ion migration path across the electrode-electrolyte boundary, thereby improving the overall rate capability of DSSCs (Venkatesan et al. 2021).

PLASMA ENGINEERING OF COUNTER ELECTRODES

Counter electrode plasma engineering in DSSCs is crucial for optimizing electrocatalytic activity, charge transfer kinetics, and overall device efficiency. Plasma engineering focuses on modifying the surface morphology and elemental composition of counter electrode materials, such as platinum, carbon materials, or metal chalcogenides, to enhance their catalytic ability in reducing oxidized redox mediators (Reza et al. 2024). This may include creating a more wettable surface, which ensures better electrolyte penetration and distribution, resulting in more homogeneous current density across the electrode surface (Lin et al. 2021). This improvement is particularly relevant for alternative counter electrode materials that often have poor catalytic activity or undesirable surface properties compared to conventional platinum electrodes (Ding et al. 2023). For example, plasma treatment can significantly improve the adhesion of carbonaceous materials to current collectors and enhance their catalytic activity by creating porous structures or doping with catalytic elements (Kanno & Honma 2025). Plasma nitriding also shows promising results in improving the performance of titanium-based current collectors and separator plates

in electrochemical systems, demonstrating potential applications in DSSCs to improve stability and efficiency (Lana et al. 2024).

HYBRID STRATEGIES

In addition to optimizing individual plasma processes, synergistic hybrid strategies that combine plasma treatment with other established modification techniques offer a promising avenue for further enhancing the performance and stability of anthocyanin-sensitive DSSCs (Pramananda, Hadyan Fityay & Misran 2021). These strategies aim to leverage the unique advantages of plasma processing, such as surface activation and defect creation, with the specific functionalities offered by molecular crosslinkers, dopants, or co-sensitizers to achieve multi-faceted improvements in dye adsorption, charge separation, and photostability (Abdulsalami et al. 2026). Similarly, the introduction of specific dopants can tune the electronic properties of the TiO_2 photoanode or the anthocyanin itself, and plasma treatment can facilitate their incorporation or activate their function to enhance charge transport and reduce recombination (Prajapat et al. 2025). Co-sensitization strategies, where plasma-treated anthocyanins are combined with other synthetic or natural dyes, can broaden the spectral absorption range and improve light harvesting efficiency, leading to higher overall photoconversion efficiency (Wang et al. 2025).

CONCLUSION

The crucial role of anthocyanin-based natural dyes as sustainable and high-potential sensitizers for application in dye-sensitized solar cells (DSSCs) with plasma-based surface modification has emerged as an innovative approach to overcome the limitations of natural dye stability and interface adhesion. Plasma treatment generates reactive oxygen and nitrogen species that can adjust surface energy, enhance hydrophilic properties, and seal surface defects without causing thermal degradation. These improved physicochemical properties enhance dye absorption, accelerate electron transport, and increase the long-term stability of the device. The integration of plasma engineering in the photoanode, electrolyte, and counter electrode also shows significant synergistic effects on the charge dynamics and operational durability of DSSCs. However, challenges related to dye degradation, pH optimization, and industrial production scale need further attention in order to commercialize this technology optimally. Further research should focus on the industrialization scale of the plasma process, optimization of treatment parameters for high reproducibility, and the application of anthocyanin-based natural dye principles in line with global sustainable energy goals (SDG 7).

ACKNOWLEDGMENTS

This project was financially supported by the Ministry of Higher Education, Malaysia under the Fundamental Research Grant Scheme (FRGS), FRGS/1/2018/TK10/UMT/02/04 (VOT 59511).

REFERENCES

- Abdulsalami, I.O., Omobhude, I.A., Abdulsalami, B.A., Younas, M., Semire, B. & Bello, I.A. 2026. Dye-sensitized solar cells: A systematic review of progress, challenges, and future perspectives. *Discover Chemistry* 3(1): 87. <https://doi.org/10.1007/s44371-026-00548-1>
- Alashti, F.J., Sohbatzadeh, F., Ahmadian, S., Kenari, R.E. & Nazifi, E. 2024. Impact of atmospheric cold plasma pretreatment on morphology, structure, and chemical properties of clove (*Syzygium aromaticum*). *LWT* 191: 115639. <https://doi.org/10.1016/j.lwt.2023.115639>
- Ali, A.H. 2022. High-performance liquid chromatography (HPLC): A review. *Annals of Advances in Chemistry* 6(1): 010-020. <https://doi.org/10.29328/journal.aac.1001026>
- Ali, H.M., Attia, M.H. & Rashed, E.N. 2024. Enhancing the stability of strawberry anthocyanins complexed to β -cyclodextrin and starch toward heat, oxidation, and irradiation. *ACS Omega* 9(5): 5319-5329. <https://doi.org/10.1021/acsomega.3c06311>
- Almutairi, F.N., Aladim, A.K. & Abdelhamid Shahat, M. 2026. Engineering interfacial charge transfer in dye-sensitized solar cells via nitrogen plasma-engineered chitosan@PVA@CuSO₄ counter electrodes. *Journal of Inorganic and Organometallic Polymers and Materials* <https://doi.org/10.1007/s10904-026-04379-6>
- Alresheedi, N.M., Ghitas, A., Almutairi, F.N. & Shahat, M.A. 2025. Optimizing the efficiency of polymer solar cells based on core-shell PAni@ZnO composites utilizing argon plasma treatment. *Journal of Inorganic and Organometallic Polymers and Materials* 35(1): 123-140. <https://doi.org/10.1007/s10904-024-03214-0>
- Alshahrie, A., Alghamdi, A.A., Hasan, P.M.Z., Ahmed, F., Albalawi, H.M.E., Umar, A. & Alsulami, A. 2022. Enhancement in the performance of dye sensitized solar cells (DSSCs) by incorporation of reduced graphene oxide (RGO) and carbon nanotubes (CNTs) in ZnO nanostructures. *Inorganics* 10(11): 204. <https://doi.org/10.3390/inorganics10110204>
- Altaf, B. & Intipunya, P. 2026. Enhancing bioactive properties of butterfly pea (*Clitoria ternatea*) extract using cold atmospheric plasma and plasma-activated water while preserving color and total solids. *Innovative Food Science and Emerging Technologies* 111: 104606. <https://doi.org/10.1016/j.ifset.2026.104606>
- Alves, L.R.P., Leal, G.F., Devos, R.J.B., Sousa, H.M.S., da Costa Gomes, C., Morais, R.A. & de Souza Martins, G.A. 2026. Anthocyanin extraction from underexplored tropical fruits: Linking plant matrix characteristics to emerging extraction technologies. *Food Bioscience* 81: 109159. <https://doi.org/10.1016/j.fbio.2026.109159>
- Amini, A., Zakerhamidi, M.S. & Khorram, S. 2021. Treatment of the ZnO and TiO₂ thin films by electric field in plasma sheath to improve the metal-dye electronic coupling in dye-sensitized solar cells. *Surfaces and Interfaces* 23: 101028. <https://doi.org/10.1016/j.surfin.2021.101028>
- Amogne, N.Y., Ayele, D.W. & Tsigie, Y.A. 2020. Recent advances in anthocyanin dyes extracted from plants for dye sensitized solar cell. *Materials for Renewable and Sustainable Energy* 9: 23. <https://doi.org/10.1007/s40243-020-00183-5>
- Amorim, D.S., Amorim, I.S., Chisté, R.C., Filho, J.T., Fernandes, F.A.N. & Godoy, H.T. 2023. Effects of cold plasma on chlorophylls, carotenoids, anthocyanins, and betalains. *Food Research International* 167: 112593. <https://doi.org/10.1016/j.foodres.2023.112593>
- Arkhangelskiy, A., Maniglio, D., Bucciarelli, A., Yadavalli, V.K. & Quaranta, A. 2021. Plasma-assisted deposition of silk fibroin on different surfaces. *Advanced Materials Interfaces* 8(13): 202100324. <https://doi.org/10.1002/admi.202100324>
- Astaneî, D., Burlică, R., Crețu, D.-E., Olariu, M.A., Stoica, I. & Beniugă, O. 2022. Treatment of polymeric films used for printed electronic circuits using ambient air DBD non-thermal plasma. *Materials* 15(5): 1919. <https://doi.org/10.3390/ma15051919>
- Avino, F., Howling, A.A., Von Allmen, M., Waskow, A., Ibba, L., Han, J. & Furno, I. 2023. Surface DBD degradation in humid air, and a hybrid surface-volume DBD for robust plasma operation at high humidity. *Journal of Physics D: Applied Physics* 56: 345201. <https://doi.org/10.1088/1361-6463/acd2e4>
- Barek, J. 2021. How to improve the performance of electrochemical sensors via minimization of electrode passivation. *Chemosensors* 9(1): 12. <https://doi.org/10.3390/chemosensors9010012>
- Benvenuti, L., Zielinski, A.A.F. & Ferreira, S.R.S. 2022. Pressurized aqueous solutions of deep eutectic solvent (DES): A green emergent extraction of anthocyanins from a Brazilian berry processing by-product. *Food Chemistry: X* 13: 100236. <https://doi.org/10.1016/j.fochx.2022.100236>
- Bertin, M., Leitao, E.M., Bickerton, S. & Verbeek, C.J.R. 2024. A review of polymer surface modification by cold plasmas toward bulk functionalization. *Plasma Processes and Polymers* 21(5): 202300208. <https://doi.org/10.1002/ppap.202300208>

- Bhushan, B., Bibwe, B., Pal, A., Mahawar, M.K., Dagla, M.C., Yathish, K.R., Jat, B.S., Kumar, P., Aggarwal, S.K., Singh, A. & Chaudhary, D.P. 2023. FTIR spectra, antioxidant capacity and degradation kinetics of maize anthocyanin extract under variable process conditions: Anthocyanin degradation under storage. *Applied Food Research* 3(1): 100282. <https://doi.org/10.1016/j.afres.2023.100282>
- Bitwell, C., Indra, S.S., Luke, C. & Kakoma, M.K. 2023. A review of modern and conventional extraction techniques and their applications for extracting phytochemicals from plants. *Scientific African* 19: e01585. <https://doi.org/10.1016/j.sciaf.2023.e01585>
- Błaszczak, A., Joachimiak-Lechman, K., Sady, S., Tański, T., Szindler, M. & Drygała, A. 2021. Environmental performance of dye-sensitized solar cells based on natural dyes. *Solar Energy* 215: 346-355. <https://doi.org/10.1016/j.solener.2020.12.040>
- Boldrini, C.L., Quivelli, A.F., Perna, F.M., Biagini, P., Capriati, V., Abbotto, A. & Manfredi, N. 2023. Top-ranked efficiency under indoor light of DSSCs enabled by iodide-based DES-like solvent electrolyte. *Sustainable Energy and Fuels* 8(3): 504-515. <https://doi.org/10.1039/d3se00949a>
- Bong, C.P.C., Hashim, H., Ho, W.S., Muis, Z.B.A., Yunus, N.A.B., Demoral, A., Tirta, A., Rizki Kresnawan, M., Safrina, R. & Rosalia, S.A. 2022. Integration of variable renewable energy, electric vehicle, and smart microgrid in ASEAN: A focus group discussion approach. *IOP Conference Series: Earth and Environmental Science* 997(1): 012013. <https://doi.org/10.1088/1755-1315/997/1/012013>
- Bosco, N., Lojen, D., Kovač, J., Zaplotnik, R., Abashidze, N., Bassolino, L., Paris, R., Montanari, M., Balestrazzi, A., Mozetič, M. & Macovei, A. 2026. Plasma-based treatments regulate seed germination in *Cannabis sativa* via oxidative status modulation and transcriptional changes. *Plant Physiology and Biochemistry* 233: 111268. <https://doi.org/10.1016/j.plaphy.2026.111268>
- Cao, X., Shen, Q., Zhuang, Y., Zhuang, G. & Chen, X. 2021. Atmospheric plasma reaction synthesised PtxFe1-x/graphene and TiO₂ nanoparticles/graphene for efficient dye-sensitized solar cells. *RSC Advances* 11(12): 6464-6471. <https://doi.org/10.1039/d0ra10067f>
- Casasanta, G., Falcini, F. & Garra, R. 2022. Beer-Lambert law in photochemistry: A new approach. *Journal of Photochemistry and Photobiology A: Chemistry* 432: 114086. <https://doi.org/10.1016/j.jphotochem.2022.114086>
- Cellura, M., Luu, L.Q., Guarino, F. & Longo, S. 2024. A review on life cycle environmental impacts of emerging solar cells. *Science of The Total Environment* 908: 168019. <https://doi.org/10.1016/j.scitotenv.2023.168019>
- Chatzimitakos, T., Athanasiadis, V., Kotsou, K., Mantiniotou, M., Kalomatsios, D., Makrygiannis, I., Bozinou, E. & Lalas, S.I. 2024. Optimization of pressurized liquid extraction (PLE) parameters for extraction of bioactive compounds from *Moringa oleifera* leaves and bioactivity assessment. *International Journal of Molecular Sciences* 25(9): 4628. <https://doi.org/10.3390/ijms25094628>
- Coad, B.R., Favia, P., Vasilev, K. & Griesser, H.J. 2022. Plasma polymerization for biomedical applications: A review. *Plasma Processes and Polymers* 19(11): 202200121. <https://doi.org/10.1002/ppap.202200121>
- de Moura, C., Vieira do Carmo, M.A., Xu, Y.Q., Azevedo, L. & Granato, D. 2024. Anthocyanin-rich extract from purple tea: Chemical stability, cellular antioxidant activity, and protection of human erythrocytes and plasma. *Current Research in Food Science* 8: 100701. <https://doi.org/10.1016/j.crfs.2024.100701>
- de Oliveira, A.A., Torres, A.G., Perrone, D. & Monteiro, M. 2021. Effect of high hydrostatic pressure processing on the anthocyanins content, antioxidant activity, sensorial acceptance and stability of jussara (*Euterpe edulis*) juice. *Foods* 10(10): 2246. <https://doi.org/10.3390/foods10102246>
- de Souza Mesquita, L.M., Contieri, L.S., Sosa, F.H.B., Pizani, R.S., Chaves, J., Viganó, J., Ventura, S.P.M. & Rostagno, M.A. 2023. Combining eutectic solvents and pressurized liquid extraction coupled in-line with solid-phase extraction to recover, purify and stabilize anthocyanins from Brazilian berry waste. *Green Chemistry* 25(5): 1884-1897. <https://doi.org/10.1039/d2gc04347e>
- Diallo, S., Melhaoui, F.Z., Rafi, M. & Ellassoudi, A. 2023. Understanding photovoltaic module degradation: An overview of critical factors, models, and reliability enhancement methods. *E3S Web of Conferences* 469: 11. <https://doi.org/10.1051/e3sconf/202346900011>
- Ding, S., Yang, C., Yuan, J., Li, H., Yuan, X. & Li, M. 2023. An overview of the preparation and application of counter electrodes for DSSCs. *RSC Advances* 13(18): 12309-12319. <https://doi.org/10.1039/d3ra00926b>
- Dudek, A., Spiegel, M., Strugała-Danak, P. & Gabrielska, J. 2022. Analytical and theoretical studies of antioxidant properties of chosen anthocyanins; A structure-dependent relationships. *International Journal of Molecular Sciences* 23(10): 5432. <https://doi.org/10.3390/ijms23105432>
- Elawady, Y.T., Elmorsy, M.R., Abdel-Latif, E., Abou El-Reash, Y.G. & Badawy, S.A. 2026. Pushing the limits of indoor photovoltaics: 25.65 % efficient tandem DSSCs with complementary N719 and piperonal sensitizers. *Dyes and Pigments* 247: 113451. <https://doi.org/10.1016/j.dyepig.2025.113451>

- Ferreira, L.F., Minuzzi, N.M., Rodrigues, R.F., Pauletto, R., Rodrigues, E., Emanuelli, T. & Bochi, V.C. 2020. Citric acid water-based solution for blueberry bagasse anthocyanins recovery: Optimization and comparisons with microwave-assisted extraction (MAE). *LWT* 133: 110064. <https://doi.org/10.1016/j.lwt.2020.110064>
- Fu, J., Xie, L., Taha, E.M., Mehanni, A.H.E., El-Shemy, H.A. & Chen, W. 2026. Anthocyanins: Structural diversity, health function, and advances in microbial biosynthesis. *Food Quality and Safety* 10: fyag027. <https://doi.org/10.1093/fqsafe/fyag027>
- Guo, J.Y., Chen, J.A., Chen, S.Y., Lee, M.L., Liu, W.R. & Kuo, Y.L. 2022. Reactive plasma oxygen-modified and nitrogen-doped soft carbon as a potential anode material for lithium-ion batteries using a tornado-type atmospheric pressure plasma jet. *Electrochimica Acta* 427: 140897. <https://doi.org/10.1016/j.electacta.2022.140897>
- Habis, C., Zaraket, J. & Aillerie, M. 2022. Transparent conductive oxides. Part II. Specific focus on ITO, ZnO-AZO, SnO₂-FTO families for photovoltaics applications. *Defect and Diffusion Forum/Diffusion and Defect Data, Solid State Data. Part A, Defect and Diffusion Forum* 417: 257-272. <https://doi.org/10.4028/p-6fqmfi>
- Hoffmann, A., Uhl, M., Ceblin, M., Rohrbach, F., Bansmann, J., Mallah, M., Heuermann, H., Jacob, T. & Kuehne, A.J.C. 2022. Atmospheric pressure plasma-jet treatment of PAN-nonwovens—carbonization of nanofiber electrodes. *C* 8(3): 33. <https://doi.org/10.3390/c8030033>
- Huang, G., Wang, K. & Markides, C.N. 2021. Efficiency limits of concentrating spectral-splitting hybrid photovoltaic-thermal (PV-T) solar collectors and systems. *Light: Science and Applications* 10(1): 28. <https://doi.org/10.1038/s41377-021-00465-1>
- Ikhsan, M.H., Putri, S.A., Anggraeni, H.R., Septiyanti, R., Hardianto, A., Latip, J. & Herlina, T. 2026. Anthocyanins from Rosaceae fruits: Diversity, bioactivity, and potential as natural colorants. *Food Chemistry: X* 34: 103606 <https://doi.org/10.1016/j.fochx.2026.103606>
- Jan, K.C. & Gavahian, M. 2024. Cold plasma at various voltage, gas flow rate, and time assisted extraction of blue pea flower: Quantitative UPLC-ESI/MS/MS analysis of bioactive compounds, phenolics, and anthocyanin content. *Innovative Food Science and Emerging Technologies* 98: 103837. <https://doi.org/10.1016/j.ifset.2024.103837>
- Jevtovic, V., Alabbosh, K.F.S., Al Shankiti, B.A., Alaskar, T.A.M., Alyami, R.A., Stankov Jovanović, V., Nikolić, J., Mašković, P. & Mitić, M. 2026. Processing-driven changes in phenolic composition and antioxidant capacity during plum wine production from the ‘Stanley’ cultivar. *Foods* 15(8): 1360. <https://doi.org/10.3390/foods15081360>
- Ji, F., Muhammad, A.I., Liao, X., Feng, J., Keener, K.M., Attanda, M.L. & Ding, T. 2026. Microbial inactivation and quality retention of blueberries using continuous in-package dielectric barrier discharge cold atmospheric plasma. *LWT* 250: 119508. <https://doi.org/10.1016/j.lwt.2026.119508>
- Kabir, F., Bhuiyan, M.M.H., Hossain, M.R., Manir, M.S., Rahaman, M.S., Islam, M.T. & Ullah, S.M. 2022. Refining of red spinach extract for the enhanced photovoltaic performance of natural dye-based DSSC and degradation study. *Optik* 251: 168452. <https://doi.org/10.1016/j.ijleo.2021.168452>
- Kang, D.Y., Kim, B., Lee, T.H., Shim, J.W., Kim, S., Sung, H., Chang, K.J. & Kim, T.G. 2021. Dopant-tunable ultrathin transparent conductive oxides for efficient energy conversion devices. *Nano-Micro Letters* 13(1): 211. <https://doi.org/10.1007/s40820-021-00735-y>
- Kanno, M. & Honma, I. 2025. Solvent-free processing of lithium-ion batteries via plasma treatment of electrodes for adhesive interfaces. *Journal of Energy Storage* 137: 118658. <https://doi.org/10.1016/j.est.2025.118658>
- Karthik, C., Chand, S. & Thomas, V. 2023. Low-temperature plasma techniques in biomedical applications and therapeutics: An overview. *International Journal of Molecular Sciences* 25(1): 524. <https://doi.org/10.3390/ijms25010524>
- Kavrut, E., Karaogul, E., Al Çiçek, S., Engin, T., Çiğdem, A., Alwazeer, D., Bekbayev, K. & Abdilova, G. 2026. Supercritical hybrid carbon dioxide-hydrogen as a new sustainable extraction of phenolics and antioxidants from grape seeds. *Applied Food Research* 6(1): 102114. <https://doi.org/10.1016/j.afres.2026.102114>
- Khosravi, S., Chaibakhsh, N., Jafari, S. & Nilkar, M. 2024. Enhanced photocatalytic activity of ZnS/TiO₂ nanocomposite by nitrogen and tetrafluoromethane plasma treatments. *Scientific Reports* 14(1): 28385. <https://doi.org/10.1038/s41598-024-78009-x>
- Kim, H.J., Kim, J., Sin, M.J. & Hong, B. 2026. Gas-specific plasma treatment of nanocrystalline TiO₂ for enhanced photovoltaic performance of DSSCs. *Materials Science in Semiconductor Processing* 214: 110911. <https://doi.org/10.1016/j.mssp.2026.110911>
- Kongklai, W., Pomkham, W. & Khat-udomkiri, N. 2026. Ultrasound-assisted polyol extraction of anthocyanins from Leumpua purple sticky rice: Cytotoxicity, antioxidant properties, anti-melanogenic and anti-tyrosinase activities, and stability evaluation. *Applied Food Research* 6(1): 102079. <https://doi.org/10.1016/j.afres.2026.102079>
- Lana, G.M., Bello, I.T., Adedokun, O.M., Adenigba, V.O., Jubu, P.R., Adedokun, O., Sanusi, Y.K., Dhlamini, M.S. & Awodugba, A.O. 2024. One-dimensional TiO₂ nanocomposite-based photoanode for dye-sensitized solar cells: A review. *Solar Energy* 279: 112850. <https://doi.org/10.1016/j.solener.2024.112850>

- Lee, D., Nam, H., Seo, M.W., Lee, S.H., Tokmurzin, D., Wang, S. & Park, Y.K. 2022. Recent progress in the catalytic thermochemical conversion process of biomass for biofuels. *Chemical Engineering Journal* 447: 137501. <https://doi.org/10.1016/j.cej.2022.137501>
- Li, J., Li, Z., Ma, Q. & Zhou, Y. 2023a. Enhancement of anthocyanins extraction from haskap by cold plasma pretreatment. *Innovative Food Science and Emerging Technologies* 84: 103294. <https://doi.org/10.1016/j.ifset.2023.103294>
- Li, X., Yang, W., Deng, J. & Lin, Y. 2023b. Surface plasmon resonance effects of silver nanoparticles in graphene-based dye-sensitized solar cells. *Frontiers in Materials* 10: 1137771. <https://doi.org/10.3389/fmats.2023.1137771>
- Lin, L., Rui, L., Li, C., Liu, Q., Li, S., Xia, Y., Hu, H., Yang, W. & Xu, H. 2021. Study on CO₂-based plasmas for surface modification of polytetrafluoroethylene and the wettability effects. *Journal of CO₂ Utilization* 53: 101752. <https://doi.org/10.1016/j.jcou.2021.101752>
- Liu, Y., Wang, Z., Li, L., Gao, S., Zheng, D., Yu, X., Wu, Q., Yang, Q., Zhu, D., Yang, W. & Xiong, Y. 2022. Highly efficient quantum-dot-sensitized solar cells with composite semiconductor of ZnO nanorod and oxide inverse opal in photoanode. *Electrochimica Acta* 412: 140145. <https://doi.org/10.1016/j.electacta.2022.140145>
- Lo, Y.H., Chen, Y.H., Huang, C.F., Pitchai, C., Liu, W.S., Chang, C.C. & Chen, C.M. 2024. A composite electrocatalytic poly(3,4-ethylenedioxythiophene) film incorporated with silver nanowires for bifacial dye-sensitized solar cells. *Electrochimica Acta* 507: 145132. <https://doi.org/10.1016/j.electacta.2024.145132>
- Lu, B.J., Lin, T.C., Chao, H.R., Tsai, C.H., Lu, J.H., Tsai, M.H., Chang, C.T., Hsieh, H., Lu, I.C., Arcega, R.D., Chang, W.H., Chen, H.L., Mansor, W.N.W. & Lee, Y.C. 2021. The impact of air or nitrogen non-thermal plasma on variations of natural bioactive compounds in djlulis (*Chenopodium formosanum* koidz.) seed and the potential effects for human health. *Atmosphere* 12(11): 1375. <https://doi.org/10.3390/atmos12111375>
- Luu, T.Q., Hayles, A., Bright, R., Palms, D., Pham, T., Truong, V.K. & Vasilev, K. 2025. Responsive biomaterials engineered via plasma-driven techniques. *Materials Today Chemistry* 49: 103036. <https://doi.org/10.1016/j.mtchem.2025.103036>
- Mahajan, U., Prajapat, K., Dhonde, M., Sahu, K. & Shirage, P.M. 2024. Natural dyes for dye-sensitized solar cells (DSSCs): An overview of extraction, characterization and performance. *Nano-Structures and Nano-Objects* 37: 101111. <https://doi.org/10.1016/j.nanoso.2024.101111>
- Mandracci, P. 2024. A review of experimental investigations into the time evolution of low-pressure capacitively coupled plasmas in their early stages of development. *Plasma* 7(3): 531-565. <https://doi.org/10.3390/plasma7030029>
- Mattioli, R., Francioso, A., Mosca, L. & Silva, P. 2020. Anthocyanins: A comprehensive review of their chemical properties and health effects on cardiovascular and neurodegenerative diseases. *Molecules* 25(17): 3809. <https://doi.org/10.3390/molecules25173809>
- Mărtiri, I., Coman, G., Cotârlet, M., Turturică, M., Balan, N., Râpeanu, G., Stănciuc, N. & Mihalcea, L. 2025. Phytochemical profile screening and selected bioactivity of *Myrtus communis* berries extracts obtained from ultrasound-assisted and supercritical fluid extraction. *Separations* 12(1): 8. <https://doi.org/10.3390/separations12010008>
- Miao, R., Chen, K., Tian, F., Du, Y. & Xu, M. 2025. Comparative evaluation of pretreatments for heat pump drying of Saimaiti apricots: Atmospheric pressure plasma jet improves drying kinetics, flavor, and nutritional quality. *Journal of Agriculture and Food Research* 24: 102535. <https://doi.org/10.1016/j.jafr.2025.102535>
- Mohammadi, M., Ishak, M.R. & Sultan, M.T.H. 2024. Exploring chemical and physical advancements in surface modification techniques of natural fiber reinforced composite: A comprehensive review. *Journal of Natural Fibers* 21(1): 2408633. <https://doi.org/10.1080/15440478.2024.2408633>
- Mohammadi, N., Franchin, M., Girotto Pressete, C., Maria Gregg Antunes, L. & Granato, D. 2024. Green recovery and application of berry anthocyanins in functional gummies: Stability study, plasma and cellular antioxidant and anti-inflammatory activity. *Food Research International* 196: 115128. <https://doi.org/10.1016/j.foodres.2024.115128>
- Moriones, J., Jiménez-Moreno, N., Ancín-Azpilicueta, C., Osés, J., de Ara, J.F., Almandoz, E. & Esparza, I. 2025. Photodegradation of rosé wines: Effects of controlled irradiation. *Food Research International* 222: 117796. <https://doi.org/10.1016/j.foodres.2025.117796>
- Mostafa, M.M., Aladim, A.K., Sebak, M.A. & Shahat, M.A. 2025. Efficient dye-sensitized solar cells (DSSCs) via nitrogen plasma-enriched Chitosan@PVA@rGO blend-based counter electrode compositions. *Journal of Inorganic and Organometallic Polymers and Materials* 35(4): 2987-3004. <https://doi.org/10.1007/s10904-024-03438-0>
- Muthukrishnan, A.P., Lee, J., Kim, J., Kim, C.S. & Jo, S. 2022. Low-temperature solution-processed SnO₂ electron transport layer modified by oxygen plasma for planar perovskite solar cells. *RSC Advances* 12(8): 4883-4890. <https://doi.org/10.1039/d1ra08946c>

- Nagao, Y., Mayumi, S., Sawamura, M., Okumura, R. & Okuya, M. 2022. Atmospheric non-equilibrium planar plasma under magnetic field to form a porous-TiO₂ layer for dye-sensitized solar cells. *Journal of the Ceramic Society of Japan* 130(4): 249-256. <https://doi.org/10.2109/jcersj2.21160>
- Ngamwonglumlert, L., Devahastin, S., Chiewchan, N. & Raghavan, G.S.V. 2020. Color and molecular structure alterations of brazilein extracted from *Caesalpinia sappan* L. under different pH and heating conditions. *Scientific Reports* 10(1): 12386. <https://doi.org/10.1038/s41598-020-69189-3>
- Oancea, S. 2021. A review of the current knowledge of thermal stability of anthocyanins and approaches to their stabilization to heat. *Antioxidants* 10(9): 1337. <https://doi.org/10.3390/antiox10091337>
- Omar, A., Ali, M.S. & Abd Rahim, N. 2020. Electron transport properties analysis of titanium dioxide dye-sensitized solar cells (TiO₂-DSSCs) based natural dyes using electrochemical impedance spectroscopy concept: A review. *Solar Energy* 207: 1088-1121. <https://doi.org/10.1016/j.solener.2020.07.028>
- Palabiyik, I., Kopuk, B., Konar, N. & Toker, O.S. 2023. Investigation of cold plasma technique as an alternative to conventional alkalization of cocoa powders. *Innovative Food Science and Emerging Technologies* 88: 103440. <https://doi.org/10.1016/j.ifset.2023.103440>
- Pan, X., Zhao, Y., Liang, S. & Wang, J. 2026. Solid electrolyte interface formation and stabilization strategies in emerging non-lithium metal ion storage systems. *MRS Energy and Sustainability* 13: 75-119. <https://doi.org/10.1557/s43581-025-00147-0>
- Panklai, T., Kumchaiseemak, N., Seelarat, W., Sangwanna, S., Chutimayanaphat, C., Bootchanont, A., Wattanawikkam, C., Rittidach, T., Boonyawan, D. & Porjai, P. 2025. Investigating effects of air-cold plasma jet on enzymatic activity and nutritional quality attributes of Mangosteen (*Garcinia mangostana* L.) juice. *Innovative Food Science and Emerging Technologies* 99: 103878. <https://doi.org/10.1016/j.ifset.2024.103878>
- Pathak, N., Grossi Bovi, G., Limnaios, A., Fröhling, A., Brincat, J.P., Taoukis, P., Valdramidis, V.P. & Schlüter, O. 2020. Impact of cold atmospheric pressure plasma processing on storage of blueberries. *Journal of Food Processing and Preservation* 44(8): e14581. <https://doi.org/10.1111/jfpp.14581>
- Piryaei, M., Shabani, S. & Alipour, K. 2026. pH-responsive intelligent edible films based on sodium alginate-pectin reinforced with chitosan nanoparticles, green-synthesized TiO₂ nanoparticles, and Azarshahr red onion peel anthocyanins. *Applied Food Research* 6(2): 102268. <https://doi.org/10.1016/j.afres.2026.102268>
- Poonthong, W., Mungkung, N., Tunlasakun, K., Thungsuk, N., Kasayapanand, N., Arunrungrusmi, S., Tanitteerapan, T., Maneepen, T., Songruk, A. & Yuji, T. 2024. Surface development of polyethylene terephthalate films using low-pressure, high-frequency argon + oxygen plasma on zinc powder for dye-sensitized solar cells. *Polymers* 16(16): 2283. <https://doi.org/10.3390/polym16162283>
- Prajapat, K., Mahajan, U., Dhonde, M., Sahu, K., Sakthivel, P., Vyas, S. & Shirage, P.M. 2025. Anthocyanin-sensitized Cu-doped TiO₂ nanoparticles for efficient and sustainable DSSCs. *Materials Advances* 6(7): 2371-2384. <https://doi.org/10.1039/d4ma01297f>
- Pramananda, V., Hadyan Fityay, T.A. & Misran, E. 2021. Anthocyanin as natural dye in DSSC fabrication: A review. *IOP Conference Series: Materials Science and Engineering* 1122(1): 012104. <https://doi.org/10.1088/1757-899x/1122/1/012104>
- Prime, G. 2022. Generation of neutral chemically reactive species in low-pressure plasma. *Frontiers in Physics* 10: 895264. <https://doi.org/10.3389/fphy.2022.895264>
- Rahman Khan, M.M., Asrafali, S.P. & Periyasamy, T. 2024. Synthesis, morphology, and biomedical applications of plasma-based polymers: Recent trends and advances. *Polymers* 16(19): 2701. <https://doi.org/10.3390/polym16192701>
- Rebohle, L., Quade, A., Schumann, T., Blaschke, D., Hübner, R., Heller, R., Foest, R., Schäfer, J. & Skorupa, W. 2022. Deposition of silicon oxide films on silicon using HelixJet - An atmospheric-pressure plasma jet process below 100 °C. *Thin Solid Films* 753: 139257. <https://doi.org/10.1016/j.tsf.2022.139257>
- Reza, M., Ilham, Setiawan, K.M., Steky, F.V., Nugroho, F.G., Agusta, M.K., Indarto, A. & Suendo, V. 2024. Microwave-plasma surface modification of nanostructured-polyaniline:graphite composite counter electrode in dye-sensitized solar cells. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 694: 134134. <https://doi.org/10.1016/j.colsurfa.2024.134134>
- Ritu, Gupta, S.K. & Negi, C.M.S. 2025. Synergistic effects of N719 and N3 dyes in DSSCs with gel polymer electrolyte and graphite counter electrode. *Next Materials* 9: 101224. <https://doi.org/10.1016/j.nxmate.2025.101224>
- Rodrigues, M.A. 2024. Anthocyanin expressed in leaves boosting chlorophyll-based dye-sensitized solar cells performance. *Next Research* 1(1): 100013. <https://doi.org/10.1016/j.nexres.2024.100013>
- Roman, H.E., Cesura, F., Maryam, R., Levchenko, I., Alexander, K. & Riccardi, C. 2024. The fractal geometry of polymeric materials surfaces: surface area and fractal length scales. *Soft Matter* 20(14): 3082-3096. <https://doi.org/10.1039/d3sm01497e>

- Russo, M., Iervolino, G., Vaiano, V. & Palma, V. 2020. Non-thermal plasma coupled with catalyst for the degradation of water pollutants: A review. *Catalysts* 10(12): 1-29. <https://doi.org/10.3390/catal10121438>
- Sakurai, Y.C.N., Pires, I.V., Ferreira, N.R., Moreira, S.G.C., da Silva, L.H.M. & da Cruz Rodrigues, A.M. 2024. Preparation and characterization of natural deep eutectic solvents (NADESs): Application in the extraction of phenolic compounds from araza pulp (*Eugenia stipitata*). *Foods* 13(13): 1983. <https://doi.org/10.3390/foods13131983>
- Santos, F., Ivanou, D. & Mendes, A. 2026. Solvent-dependent charge transfer dynamics under indoor light in efficient and stable copper-mediated DSSCs. *ACS Applied Energy Materials* 9(13): 8868-8878. <https://doi.org/10.1021/acsaem.6c01356>
- Sebak, M.A., Aladim, A.K., Mostafa, M. & Shahat, M.A. 2025. Multi-level oxygen plasma treatment nanoarchitectonics on chitosan/PVA/TiO₂ composite-based absorber layer network for efficient polymer solar cells. *Journal of Inorganic and Organometallic Polymers and Materials* 35(6): 4570-4588. <https://doi.org/10.1007/s10904-024-03542-1>
- Settapramote, N., Utama-Ang, N., Petiwathayakorn, T., Settakorn, K., Svasti, S., Srichairatanakool, S. & Koonosying, P. 2021. Antioxidant effects of anthocyanin-rich riceberry™ rice flour prepared using dielectric barrier discharge plasma technology on iron-induced oxidative stress in mice. *Molecules* 26(16): 4978. <https://doi.org/10.3390/molecules26164978>
- Shahat, M.A., Ghitas, A., Almutairi, F.N. & Alresheedi, N.M. 2024. Oxygen enriched PANi-based counter electrode network toward efficient dye-sensitized solar cells (DSSCs). *Scientific Reports* 14(1): 25977. <https://doi.org/10.1038/s41598-024-67055-0>
- Spadaro, D., Barichello, J., Citro, I. & Calogero, G. 2023. Environmentally friendly water-based electrolyte for dye-sensitized solar cells: Future prospective and outlook. *Solar* 3(2): 229-252. <https://doi.org/10.3390/solar3020015>
- Srivastava, K.V., Srivastava, A., Maurya, R.K., Singh, Y.P. & Srivastava, A. 2025. Synergistic effect of anthocyanin-rich *Euphorbia milii* dye and TiCl₄-passivation on 1D TiO₂-based DSSCs. *Next Materials* 9: 100945. <https://doi.org/10.1016/j.nxmate.2025.100945>
- Tan, J., Han, Y., Han, B., Qi, X., Cai, X., Ge, S. & Xue, H. 2022. Extraction and purification of anthocyanins: A review. *Journal of Agriculture and Food Research* 8: 100306. <https://doi.org/10.1016/j.jafr.2022.100306>
- Tao, B., Qian, Z., Miao, F. & Zhang, P. 2025. Preparation and characterization of high-efficiency plasma dye-sensitized cell photoanode based on Cu/CuO/TiO₂ ternary composite material. *Microchimica Acta* 192(9): 555. <https://doi.org/10.1007/s00604-025-07355-y>
- Taveepanich, S., Chayajarus, K., Jittimane, J., Phusri, N., Thongdee, P., Sawatdee, K., Kamsri, P., Punkvang, A., Suttisintong, K., Pungpo, P., Suwannaloet, W., Thongrungs, R. & Pangjit, K. 2024. Iron chelating, antioxidant, and anti-inflammatory properties of brazilin from *Caesalpinia sappan* Linn. *Heliyon* 10(19): e38213. <https://doi.org/10.1016/j.heliyon.2024.e38213>
- Thakker, A.M., Sun, D. & Bucknall, D.G. 2022. Inkjet printing of plasma surface-modified wool and cotton fabrics with plant-based inks. *Environmental Science and Pollution Research* 29(45): 68357-68375. <https://doi.org/10.1007/s11356-022-20659-3>
- Thakur, A., Kumar, A., Kaya, S., Marzouki, R., Zhang, F. & Guo, L. 2022. Recent advancements in surface modification, characterization and functionalization for enhancing the biocompatibility and corrosion resistance of biomedical implants. *Coatings* 12(10): 1459. <https://doi.org/10.3390/coatings12101459>
- Thomas, S.N., French, D., Jannetto, P.J., Rappold, B.A. & Clarke, W.A. 2022. Liquid chromatography-tandem mass spectrometry for clinical diagnostics. *Nature Reviews Methods Primers* 2(1): 96. <https://doi.org/10.1038/s43586-022-00175-x>
- Tiwari, A., Srivastav, N. & Srivastava, P. 2024. Utilization of natural dyes extracted from mustard flower (Genus: Brassica, Species: Napus) as photosensitizer for DSSC: Experimental and computational studies. *Results in Optics* 15: 100631. <https://doi.org/10.1016/j.rio.2024.100631>
- Udomkun, P., Romuli, S., Schock, S., Mahayothee, B., Sartas, M., Wossen, T., Njukwe, E., Vanlauwe, B. & Müller, J. 2020. Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. *Journal of Environmental Management* 268: 110730. <https://doi.org/10.1016/j.jenvman.2020.110730>
- Ullah, M.H., Akther, H., Rahman, M.M., Foisal, A.B.M., Hasan, M.M., Amir-Al Zumahi, S.M. & Amri, A. 2021. Surface modification and improvements of wicking properties and dyeability of grey jute-cotton blended fabrics using low-pressure glow discharge air plasma. *Heliyon* 7(8): e07893. <https://doi.org/10.1016/j.heliyon.2021.e07893>
- Urbstaite, R., Raudone, L. & Janulis, V. 2022. Phyto-genotypic anthocyanin profiles and antioxidant activity variation in fruit samples of the American cranberry (*Vaccinium macrocarpon* Aiton). *Antioxidants* 11(2): 250. <https://doi.org/10.3390/antiox11020250>
- Vannuchi, N., Braga, A.R.C. & De Rosso, V.V. 2022. High-performance extraction process of anthocyanins from jussara (*Euterpe edulis*) using deep eutectic solvents. *Processes* 10(3): 615. <https://doi.org/10.3390/pr10030615>

- Vannuchi, N., dos Passos Ramos, S., Mazzo, T.M., Longo, E., Bonsanto, F.P., Braga, A.R.C. & de Rosso, V.V. 2024. Natural deep eutectic solvents (NADES)-extracted anthocyanins: Bioaccessibility in electrospun PEO microfibers. *Food Research International* 177: 113898. <https://doi.org/10.1016/j.foodres.2023.113898>
- Venkatesan, S., Chen, Y.Y., Chien, C.Y., Tsai, M.H., Teng, H. & Lee, Y.L. 2021. Quasi-solid-state composite electrolytes with Al₂O₃ and ZnO nanofillers for dye-sensitized solar cells. *Electrochimica Acta* 380: 137588. <https://doi.org/10.1016/j.electacta.2020.137588>
- Vinh, P.T., Hanh, V.T. & Tra, P.T. 2026. Optimizing anthocyanin extraction and sensory quality of roasted black bean tea using quadratic modeling and response surface methodology. *Applied Food Research* 6(1): 102248. <https://doi.org/10.1016/j.afres.2026.102248>
- Višnjevec, A.M., Barp, L., Lucci, P. & Moret, S. 2024. Pressurized liquid extraction for the determination of bioactive compounds in plants with emphasis on phenolics. *TrAC - Trends in Analytical Chemistry* 173: 117620. <https://doi.org/10.1016/j.trac.2024.117620>
- Wang, L., Wang, R., Dong, J., Wang, Y., Huang, X. & Chen, C. 2023. Research on the extraction, purification and determination of chemical components, biological activities, and applications in diet of black chokeberry (*Aronia melanocarpa*). *Chinese Journal of Analytical Chemistry* 51(10): 100301. <https://doi.org/10.1016/j.cjac.2023.100301>
- Wang, X., Hou, M., Liu, T., Ren, J., Li, H., Yang, H., Hu, Z. & Gao, Z. 2025. Continuous cold plasma reactor for the processing of NFC apple juice: Effect on quality control and preservation stability. *Innovative Food Science and Emerging Technologies* 100: 103905. <https://doi.org/10.1016/j.ifset.2024.103905>
- Wang, Y., Zhao, L., Zhang, R., Yang, X., Sun, Y., Shi, L. & Xue, P. 2020. Optimization of ultrasound-assisted extraction by response surface methodology, antioxidant capacity, and tyrosinase inhibitory activity of anthocyanins from red rice bran. *Food Science and Nutrition* 8(2): 921-932. <https://doi.org/10.1002/fsn3.1371>
- Waode Sukmawati Arsyad, Rizal Suhardiman, Ida Usman, La Aba, Suryani Suryani, La Ode Ahmad Nur Ramadhan, Muh. Nurdin & Rahmat Hidayat. 2024. Improvement of dye-sensitized solar cells (DSSCs) performance using crude brazilein extract from sappanwood (*Caesalpinia sappan* L.) with the incorporation of ZnO nanoparticles. *Journal of Molecular Structure* 1303: 137548. <https://doi.org/10.1016/j.molstruc.2024.137548>
- Wante, H.P., Aidan, J. & Ling, Y.S. 2024. Highly improved efficiency of flexible dye sensitized solar cells (DSSCs) by non-thermal plasma processing of PEI-ITO polymer. *Optical Materials* 150: 115331. <https://doi.org/10.1016/j.optmat.2024.115331>
- Wante, H.P., Aidan, J. & Ezike, S.C. 2021. Efficient dye-sensitized solar cells (DSSCs) through atmospheric pressure plasma treatment of photoanode surface. *Current Research in Green and Sustainable Chemistry* 4: 100218. <https://doi.org/10.1016/j.crgsc.2021.100218>
- Weerasinghe, J., Sen, S., Kumari, J.M.K.W., Dissanayake, M.A.K.L., Senadeera, G.K.R., Thotawatthage, C.A., Ekanayake, M., Zhou, R., Cullen, P.J., Sonar, P., Vasilev, K. & Ostrikov, K(K). 2021. Efficiency enhancement of low-cost metal free dye sensitized solar cells via non-thermal atmospheric pressure plasma surface treatment. *Solar Energy* 215: 367-374. <https://doi.org/10.1016/j.solener.2020.12.044>
- Wong, X.W., Lee, Y.H., Venkatesan, S., Ho, K.C., Teng, H. & Lee, Y.L. 2025. Quasi-solid-state dye-sensitized solar cells with over 36% efficiency achieved by a direct-contact cell structure and *in situ* gelation of copper-based electrolytes. *ACS Sustainable Chemistry and Engineering* 13(9): 3432-3440. <https://doi.org/10.1021/acssuschemeng.4c07717>
- Wu, Y., Zhang, D., Dong, P., Li, F., Zhou, Y., Wang, X., Zhou, H. & Liang, F. 2025. Dielectric barrier discharge plasma-assisted silicon oxide interface engineering for long-cycling stability of sodium-ion batteries at high rates. *Chemical Engineering Journal* 520: 165759. <https://doi.org/10.1016/j.cej.2025.165759>
- Xu, L., Gao, Z., Li, L. & Guo, J. 2024. Impact of dielectric barrier discharge cold plasma on anthocyanin metabolism in blueberries: A targeted metabolomic and transcriptomic analysis. *Postharvest Biology and Technology* 213: 112963. <https://doi.org/10.1016/j.postharvbio.2024.112963>
- Yang, L., Zhu, Y., Liu, J., Chen, Y., Wu, J., Pang, Z., Lu, Z., Zhao, S. & Huang, Y. 2021. Marked effects of azulenyl vs. naphthyl groups on donor- π -acceptor- π -donor small molecules for organic photovoltaic cells. *Dyes and Pigments* 187: 109079. <https://doi.org/10.1016/j.dyepig.2020.109079>
- Yiğit, Ü., Turabi Yolaçaner, E., Hamzalıoğlu, A. & Gökmen, V. 2022. Optimization of microwave-assisted extraction of anthocyanins in red cabbage by response surface methodology. *Journal of Food Processing and Preservation* 46(1): e16120. <https://doi.org/10.1111/jfpp.16120>

- Yusufoğlu, B., Gundogan, R., Ayık, Y., Görlitz, O., Atalay, V.E., Capanoglu, E. & Esatbeyoglu, T. 2026. Effect of soybean protein isolate-*Aronia melanocarpa* extract interaction on the bioaccessibility of anthocyanins after low-pressure cold plasma treatment. *Food Chemistry: X* 37: 104000. <https://doi.org/10.1016/j.fochx.2026.104000>
- Zhang, C., Ding, W., Mamattursun, A., Ma, X., Qi, S., Wu, Y., Zhang, J. & Ma, X. 2025. Optimization of enzyme-ultrasound assisted extraction from mulberries anthocyanins based on response surface methodology and deep neural networks and analysis of *in vitro* antioxidant activities. *Food Chemistry* 478: 143597. <https://doi.org/10.1016/j.foodchem.2025.143597>
- Zhang, S., Lin, S., Zhang, J. & Liu, W. 2024. Ultrasound-assisted natural deep eutectic solvent extraction of anthocyanin from *Vitis davidii* Foex. pomace: Optimization, identification, antioxidant activity and stability. *Heliyon* 10(12): e33066. <https://doi.org/10.1016/j.heliyon.2024.e33066>
- Zhang, X., Wang, S., Wu, Q., Battino, M., Giampieri, F., Bai, W. & Tian, L. 2022. Recovering high value-added anthocyanins from blueberry pomace with ultrasound-assisted extraction. *Food Chemistry: X* 16: 100476. <https://doi.org/10.1016/j.fochx.2022.100476>