A comprehensive review of coconut liquid endosperm (*Cocos nucifera* L.): Composition, physicochemical characteristics, antimicrobial and antioxidant properties, and applications in microbial and tissue culture media

S Shayanthavi[1*], R Kapilan[2], Indira Wickramasinghe[1]

[1]Department of Food Science and Technology, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.
[2] Department of Botany, Faculty of Science, University of Jaffna, Sri Lanka

*Corresponding author: shayanthavi@sci.sjp.lk

https://orcid.org/0000-0003-1124-7271

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Abstract Coconut (*Cocos nucifera*. L) endosperm, particularly in its liquid form, commonly known as coconut water, is gaining attention due to its diverse composition and potential applications in microbial and tissue culture media. This review provides a comprehensive overview of the composition and characteristics of coconut water, emphasizing its antimicrobial and antioxidant properties relevant to microbial and tissue culture applications. The composition of coconut water, including sugars, vitamins, minerals, amino acids, phytochemicals, enzymes, and phytohormones, has been reviewed. These components vary based on factors such as coconut varieties, growing conditions, and maturity stages. Furthermore, the review explores the antimicrobial attributes of coconut water, suggesting its potential as a viable substitute for conventional culture media in microbial growth. Coconut water can be used in callus production and shoot regeneration in tissue culture due to plant growth-promoting factors such as auxins, cytokinins, and gibberellins. The significance of coconut water as a valuable resource for developing effective and sustainable microbial and tissue culture media, while also identifying avenues for further research and application development in this field.

Keywords: Antimicrobial properties, Antioxidant, Coconut water, Microbial media, Phytohormones

Introduction

The coconut palm (*Cocos nucifera* L.) is a monocotyledonous plant of the family Arecaceae, extensively cultivated in over 93 tropical countries. It plays a vital role in agriculture, particularly in coastal and island ecosystems, and is recognised as the "tree of life" due to its wide-ranging utility and socio-economic value. Coconut is considered the principal export crop in the Pacific region (Kalina & Navaratne, 2019). Globally, major coconut-producing countries include Indonesia, India, the Philippines, Brazil, Sri Lanka, Papua New Guinea, Vietnam, Mexico, Thailand, and Malaysia. In 2021, Indonesia, India, and the Philippines together accounted for a significant proportion of global coconut production (Rethinam & Krishnakumar, 2022). The global rise in demand has prompted initiatives to develop high-yielding hybrid seedlings, ensuring sustainability and long-term productivity in coconut cultivation. Coconut-derived products have gained growing importance in international trade. In 2014, the Philippines and Sri Lanka were among the major exporters of activated carbon produced from coconut shells (Hoe, 2018).

In addition to its economic value, *Cocos nucifera* is highly versatile; nearly every part of the palm is utilised in daily life, serving a wide range of purposes, including food, fuel, construction materials, and other essential applications. The fruit of the coconut palm, botanically classified as a drupe, is roughly spherical and comprises three principal layers, including the fibrous outer husk (exocarp and mesocarp), a hard inner shell (endocarp), and a central cavity that contains the developing endosperm (Prithviraj et al., 2021). During the maturation of the fruit, the endosperm progresses through two distinct stages. In the early developmental phase, it exists in a liquid form known as coconut water (CW), which begins to accumulate approximately two months after flowering. This clear, sterile liquid fills the central cavity and serves as a nutrient reservoir that supports the growth of the developing embryo. As the fruit matures, a significant portion of the liquid endosperm solidifies to form the white, fleshy kernel commonly referred to as coconut meat that is particularly rich in fats and other vital nutrients. Unlike cereal crops such as wheat or maize, whose endosperms primarily form through cellular development, the coconut's endosperm uniquely persists in a liquid state during early development. Both the liquid and solid forms of the coconut endosperm are recognised for their high concentrations of nutritional and bioactive compounds. These components contribute significantly to the traditional diets of tropical populations, offering not only sustenance but also a range of health-promoting benefits. Furthermore, the unique biochemical composition and physiological functions of coconut water have attracted growing scientific and commercial interest, particularly in the context of natural health products and functional beverages (Solangi & Iqbal, 2011; Sathiyavimal et al., 2014).

This unique composition supports its role as an effective hydrating agent and a natural alternative to conventional energy and electrolyte sources (Santos et al., 2013). Laboratory studies have demonstrated the successful use of coconut water as a short-term intravenous hydration fluid, such as for a patient from the Solomon Islands (Campbell-Falck et al., 2000). The potential of coconut water as a rehydration fluid gained attention during a cholera outbreak in Tarawa, Gilbert Islands, in 1979 (Kuberski et al., 1979). Beyond rehydration, tender coconut water (TCW) has been recommended for treating urinary stones and gastroenteritis. Furthermore, consumption of coconut water has shown benefits in cardiovascular health, with studies suggesting it may prevent isoproterenol-induced myocardial infarction (Anurag & Rajamohan, 2003) and significantly reduce systolic and diastolic blood pressure (Alleyne et al., 2005). Additionally, six-month-old young coconut water contains compounds that resemble estrogen and may protect against neurodegenerative disorders such as Alzheimer's disease in menopausal women. For young women experiencing menstrual pain, drinking young coconut water has been shown to alleviate symptoms. According to a study by Wulan et al. (2019), the menstrual pain scale decreased from a range of 3–7 (indicating moderate to severe pain) to 0–5 (no pain to moderate discomfort) following the consumption of tender coconut water.

Despite its numerous health and nutritional benefits, the short shelf life of coconut water (CW) significantly limits its commercial potential. Due to its high sugar content and the presence of active plant enzymes, tender coconut water is particularly prone to rapid microbial and enzymatic spoilage. This presents a major challenge for its widespread use in the food and beverage industry. Therefore, extending the shelf life of CW without compromising its sensory and nutritional qualities remains a critical technological challenge. Recent advancements in non-thermal preservation technologies, such as cold sterilisation and microfiltration, have shown promise in addressing this issue by enhancing the stability of coconut water for storage and transportation (Masa et al., 2007; Appaiah et al., 2015). These innovations are crucial for ensuring that the commercial potential of coconut water is fully realised while maintaining its health benefits.

The use of coconut water as a microbial growth medium has been recognised for decades. As early as the 1960s, it was observed to support the growth of specific bacteria, notably those involved in the production of *nata de coco*, a bacterial cellulose that forms at the interface of coconut water and air. Originating in the Philippines, this fermented product has since become popular in various Asian countries. The bacterium responsible, later identified as *Acetobacter xylinum*, is known for its cellulose-producing capacity (Prades et al., 2012). Coconut water’s suitability for microbial fermentation also led to its traditional use in producing coconut vinegar and coconut wine. These early applications highlight the long-standing appreciation of coconut water as a natural growth medium.

In recent years, this recognition has expanded beyond traditional uses, as coconut water gains prominence in biological and biotechnological research. Its naturally sterile nature, coupled with a rich composition of nutrients, minerals, and endogenous phytohormones, makes it an effective and economical alternative to conventional synthetic media. In plant tissue culture, both coconut water (from the liquid endosperm) and coconut milk (extracted from the solid endosperm) have been widely utilised to promote cell division, stimulate callus induction, and enhance organogenesis (Molnar et al., 2011). Numerous studies have demonstrated their ability to support microbial proliferation and plant regeneration across a range of species. These characteristics underscore their potential in developing cost-effective media, particularly in regions where access to commercial culture components is limited.

This review aims to provide a comprehensive overview of coconut liquid endosperm, focusing on its composition, physicochemical characteristics, antimicrobial and antioxidant properties, and its emerging role in microbial and tissue culture media, thereby establishing its significance in both academic research and industrial applications.

Composition of coconut water

The composition of coconut water is complex and varies depending on several factors. While it is broadly recognised for its nutritional, medicinal, and physiological value, its specific chemical profile can differ based on the maturity stage of the nut, the coconut variety, and various external conditions. Geographical location, soil type, climate, and other environmental factors have been shown to influence the concentration of key constituents. Generally, coconut water contains a mixture of macronutrients such as carbohydrates, proteins, and fats, alongside micronutrients including vitamins and minerals. It also holds a range of biologically active compounds such as enzymes, phytochemicals and plant growth regulators. Each of these elements contributes to the functional and nutritional benefits of coconut water, making it a valuable natural resource (Franco et al., 2015). Table 1 summarises the macronutrient and micronutrient composition of coconut liquid endosperm (*Cocos nucifera* L.) as reported in various studies.

Water

Liquid endosperm is primarily composed of water, making it an effective hydrating beverage. It typically accounts for around 95% of its total composition, varying slightly depending on the maturity of the coconut and the coconut variety. Its purity and sterility within the unopened coconut also make it a unique plant-based fluid, often considered biologically similar to intracellular fluids due to its electrolyte balance and isotonic properties. This has led to its use in oral rehydration and, historically, even in intravenous hydration in emergency situations (Kuberski et al., 1979). In young (tender) coconuts, the water content is at its highest, whereas in mature coconuts, the volume decreases and the composition becomes more concentrated. As a result, coconut water appears as a clear liquid at the early stage but becomes turbid as the fruit matures (Kumar et al., 2021).

Carbohydrates

Sugars are key macronutrients in coconut water, contributing to its natural sweetness and energy-providing properties. The major sugars present include glucose, fructose, and sucrose, with glucose and fructose being the predominant reducing sugars in young coconuts. As the coconut matures, there is a substantial increase in sucrose, a non-reducing sugar, while the concentrations of glucose and fructose decline. This shift is attributed to the enzymatic synthesis of sucrose from glucose and fructose during maturation (Sekar et al., 2013). The changes in sugar composition not only reflect the developmental stage of the coconut but also influence its osmotic properties, enhancing its potential as a rehydrating agent. Total soluble solids, largely composed of these sugars and organic acids, are directly linked to the perceived sweetness and flavour profile of coconut water (Lemos et al., 2023). Consequently, the variation in sugar content across different stages of maturity affects both its nutritional value and sensory appeal, reinforcing coconut water's reputation as a natural isotonic beverage, particularly in tropical climates. As reported by Sarker et al. (2022), HPLC-refractive index analysis chromatograms for reducing sugars, such as dextrose and fructose, reveal fluctuations in sugar concentrations during maturation. For example, fructose concentrations ranged from 2.30 ± 0.16, 2.98 ± 0.44, to 1.65 ± 0.18 g/100 ml at 4, 6, and 8 months of age, respectively. Similarly, dextrose concentrations were 2.40 ± 0.30, 4.02 ± 0.39, and 2.65 ± 0.08 g/100 ml, highlighting the variations in sugar composition as the coconut matures.

Fat content

Coconut water is typically regarded as a low-fat beverage, although the fat content can vary significantly depending on the coconut's maturity and variety. As coconuts mature, the crude fat content of the water generally increases, primarily due to the greater development of the fleshy portion of the nut. Jackson et al. (2004) noted that the fat content rises with increasing maturity. For instance, Wynn (2017) reported that mature coconut water contains 0.18% fat, while immature coconut water has a lower fat content of 0.12%. According to Appaiah et al. (2015), the fat content of tender coconut water (0.2 ± 0.01–0.4 g/100 mL) is significantly lower than that of mature coconut water (1.2 g/100 ml), indicating a significant increase in fat concentration with maturity. Despite these variations, coconut water consistently contains much lower fat levels compared to coconut meat, which is rich in lipids. Moreover, the lipid content of coconut water can also vary among different coconut varieties. Santos et al. (2013) reported substantial differences in lipid concentrations among several coconut varieties. For example, the Green Dwarf variety contains approximately 428.7 mg/dL of lipids, while the Yellow Dwarf, Red Dwarf, and Yellow Malaysian varieties contain 222 mg/dL, 233.1 mg/dL, and 392.7 mg/dL, respectively. The fat content in coconut water shows clear variation among different varieties.

For example, the fat content was recorded as 0.1720 ± 0.0209% in the dwarf variety (CWD), 0.3350 ± 0.021% in the tall variety (CWT), and San Ramon (CWS) (Coulibaly et al., 2023).

These findings highlight the influence of both coconut variety and maturity on the fat content of coconut water, suggesting that these factors must be carefully considered when assessing its nutritional composition

Protein

Coconut water contains only small amounts of protein. Generally, protein levels tend to increase as the coconut matures. Wynn (2017) reported that immature coconut water contains approximately 0.13% protein, which increases to 0.31% in mature coconuts. Jackson et al. (2004) also observed variability in protein levels across different varieties at around seven months of age, with values ranging from 0.02% to 0.08%. More recent findings by Kumar et al. (2021) demonstrated that soluble protein content in 5–6-month-old coconuts of the Chowghat Orange Dwarf and Malayan Yellow Dwarf varieties ranged from 5 to 10 mg BSA/100 ml, highlighting varietal differences even at similar stages of maturity.

Shayanthavi et al. (2024) further reported that among selected Sri Lankan varieties, King coconut exhibited significantly higher protein content, while the CRIC 65 variety had the lowest. Coulibaly et al. (2023) also confirmed variation in protein content among different varieties, with values ranging between 0.116% and 0.291%. Although coconut water generally contains far less protein than coconut meat, it is noted for containing the amino acid L-arginine, which may contribute to cardiovascular health (Prado et al., 2015). These findings collectively highlight the importance of considering both varietal and maturity-related factors when evaluating the protein content and nutritional potential of coconut water.

Vitamins

Coconut water contains a range of water-soluble vitamins, primarily from the B-complex group and vitamin C. Among these, vitamins B3 (niacin), B5 (pantothenic acid), and B6 (pyridoxine) are commonly detected in measurable amounts, while others, such as B1 (thiamine), B2 (riboflavin), B7 (biotin), and B9 (folate)are present in trace amounts. These B vitamins are essential as coenzymes in numerous metabolic processes that support cellular function (Yong et al., 2009). Vitamin C, also known as ascorbic acid, is the most abundant vitamin in coconut water and plays a vital role in immune defence, iron absorption, collagen synthesis, and tissue repair. Its antioxidant properties also help neutralise harmful byproducts during viral infections (Tuyekar et al., 2021).

However, the concentration of vitamin C in coconut water tends to decrease as the coconut matures (Santosa et al., 1996), a reduction possibly due to the natural transfer of nutrients from the liquid to the developing solid endosperm (flesh), oxidative degradation of ascorbic acid over time, and a shift in the coconut's metabolic activity towards nutrient storage. Consequently, younger coconuts typically contain higher levels of vitamin

C, making tender coconut water particularly valued for its nutritional and health-promoting properties. Ortutu et al. (2024) reported a slight increase in vitamin C concentration with coconut maturity. Specifically, mature coconuts contained 7.46 mg/100g of vitamin C, compared to 6.82 mg/100g in immature coconuts, indicating a modest rise in vitamin C levels as the coconut develops. This variation may be attributed to differences in coconut variety, growing conditions, or measurement techniques.

Minerals

Coconut water is a rich source of essential minerals, particularly electrolytes such as potassium, sodium, magnesium, and calcium, which contribute to its classification as a natural isotonic beverage. These electrolytes play vital physiological roles, including regulating fluid balance, supporting nerve transmission, and maintaining cardiovascular health. Among them, potassium is present in the highest concentration and is essential for maintaining osmotic balance across cell membranes. It also plays a therapeutic role in preventing kidney stone formation by aiding in the dissolution of mineral aggregates (Wynn, 2017).

The mineral composition of coconut water varies significantly depending on both the maturity stage and the variety of the coconut. For instance, Solangi and Iqbal (2011) reported that hybrid coconuts at 11–12 months maturity exhibited the highest sodium content in the water (52.96 mg/kg), while the same maturity stage of coconut meat had the lowest sodium level (8.33 mg/kg). Similarly, calcium content was found to be highest in the water of the Sri Lanka Tall variety at 6–7 months maturity (4377.21 mg/kg) and lowest in the hybrid variety of the same age (184.3 mg/kg). This highlights the influence of varietal differences and physiological maturity on mineral distribution.

Magnesium, another abundant mineral in coconut water, is crucial for neuromuscular function and exhibits cardioprotective properties. Furthermore, the naturally balanced electrolyte profile of coconut water has been associated with the regulation of blood pressure, making it a valuable dietary component for managing hypertension. Although present in much lower concentrations, iron content in coconut water ranges from 0.246 to 0.938 ppm, while toxic elements such as cadmium and arsenic are typically undetectable (Anurag & Rajamohan, 2003).

According to Ortutu et al. (2024), immature coconut water generally contains higher levels of most minerals compared to mature coconut water. Calcium, magnesium, phosphorus, sodium, and zinc concentrations were higher in immature coconuts (3.05, 0.84, 12.10, 3.75, and 0.04 mg/100 g, respectively) than in mature ones (2.71, 0.56, 4.66, 3.08, and 0.02 mg/100 g). However, potassium and copper were slightly more abundant in mature coconut water (28.64 and 0.12 mg/100 g, respectively) than in immature samples (28.00 and 0.09 mg/100 g). The Na/K ratio also increased slightly from 0.11 in mature to 0.13 in immature coconuts, while the Ca/P ratio decreased from 0.58 to 0.25, reflecting shifts in mineral balance during maturation (Ortutu et al., 2024).

In dwarf coconut palms grown in non-coastal regions, a decline in potassium, calcium, magnesium, and chloride levels was observed as the coconut matured from the sixth to the ninth month. This trend suggests a gradual shift in nutrient distribution during endosperm development. Potassium remained the most abundant mineral, although its concentration decreased with age. These findings contrast with other studies where mineral levels, particularly potassium, remained relatively stable across different geographical locations, such as coastal and inland regions (Vigliar et al., 2006). Therefore, both varietal traits and environmental conditions play significant roles in shaping the mineral profile of coconut water during maturation.

Table 1. Macronutrient and micronutrient composition of coconut liquid endosperm (*Cocos nucifera* L.) reported from various studies.

Nutrients	Value	Variety	Maturity stage	Reference
Reducing sugar	3.04 – 4.83 % 3.48 – 4.41 %	Green dwarf Orange dwarf	7-9 month old	Jackson et al., 2004
Non reducing sugar	0.28 – 1.44 % 0.89 – 1.14 %	Green dwarf Orange dwarf	7-9 month old	Jackson et al., 2004
Protein	0.04 % 0.05 %	Hainan tall	8 month old 10 month old	Zhang et al., 2024
Fats	0.07 % 0.39 %	Hainan tall	8 month old 10 month old	Zhang et al., 2024
Potassium	1284 mg/L 1221 mg/L 1269 mg/L	Sri Lankan tall Malayan Hybrid	6-7 month old	Chidambaram et al., 2013
Sodium	43.27 mg/L 54.43 mg/L 64.00 mg/L	Malayan tall Aromatic dwarf Hybrid	5-6 month old	Asad et al., 2022
Calcium	4.2 mg/100 ml 3.8 mg/100 ml	Chowghat orange dwarf Malayan Yellow Dwarf	5-6 month old	Kumar et al., 2020
Magnesium	4.2 mg/100 ml 4.0 mg/100 ml	Chowghat orange dwarf Malayan Yellow Dwarf	5-6 month old	Kumar et al., 2020
Chloride	48.7 mEq/L 36.3 mEq/L	Dwarf coconut	6 month old 7 month old	Vigliar et al., 2006
Iron	0.294 mg/ml 0.308 mg/ml	Malayan tall	5-6 month old 8-9 month-old	Tan et al., 2014a
Vitamin C	30.18 µg/ml 19.10 µg/ml	Malayan green Malayan yellow	9 month-old	Adubofuor et al., 2016
Vitamin B5	Nearly 0.00785 mg/ 100g	Makapuno coconut	10 month-old	Phonphoem et al., 2022
Vitamin B3	Nearly 0.007555 mg/ 100g	Makapuno coconut	10 month-old	Phonphoem et al., 2022

Enzymes

Enzymes naturally present in coconut water, particularly polyphenol oxidase (PPO) and peroxidase (POD), play significant roles in determining its post-harvest quality and stability. These oxidative enzymes contribute to enzymatic browning, which can lead to undesirable pink discolouration during storage and processing. Such enzymatic reactions are influenced by both the maturity stage and varietal differences in coconuts. polyphenol oxidase activity tends to be higher in immature coconuts, while peroxidase activity increases with maturity (Tan et al., 2014b). Garcia et al. (2007) reported that coconut water from seven-month-old coconuts exhibited increased enzyme activity and visible pinking, whereas coconuts harvested at nine or ten months showed minimal to no discolouration, suggesting reduced enzymatic activity at later stages of development.

Enzymatic behaviour also varies between coconut varieties. Some varieties naturally exhibit higher levels of PPO or POD, making them more susceptible to oxidation and colour change. While detailed comparative studies across all cultivars remain limited. Although heat treatment can inactivate these enzymes (Matsui et al., 2008), it may compromise the sensory and nutritional qualities of coconut water. Interestingly, PPO has been shown to be more heat-resistant than POD (Tan et al., 2014a).

Recent advancements have explored non-thermal approaches to enzyme control. For example, ozone processing has been shown to inactivate POD effectively without degrading beneficial phenolic compounds, offering a promising alternative to thermal treatments (Porto et al., 2020). Furthermore, certain phenolics in coconut water may act as natural PPO inhibitors, though this interaction may vary with cultivar and harvest time.

Phenolic compounds

Phenolic compounds are one of the major classes of bioactive constituents in coconut water, contributing to its functional and therapeutic properties. These secondary metabolites, primarily involved in plant defence and structural integrity, are present in varying concentrations depending on the coconut variety and stage of maturity.

Recent studies reveal that the total phenolic content (TPC) in coconut water can differ markedly among cultivars. For instance, Coulibaly et al. (2023) observed notable differences in phenolic composition among samples from different coconut types, with the dwarf variety (CWD) exhibiting the highest levels of both total phenols and flavonoids, measured at 0.177 ± 0.001 µg/mL GAE and 0.381 ± 0.010 µg/mL QE, respectively. Similarly, Shayanthavi et al. (2024) reported significantly higher TPC in Ran thembili (28.12 ± 2.12 µg GAE/mL) and King coconut (26.25 ± 1.9 µg GAE/mL), while lower values were noted in Nawasi, CRIC 60, and CRIC 65, ranging between 18.32 and 20.18 µg GAE/mL.

Earlier findings by Santos et al. (2013) further emphasise varietal influence, showing a broad range in TPC values among Green dwarf (99.4 µg/mL), Yellow dwarf (23.8 µg/mL), and Red dwarf (18.4 µg/mL) coconuts. These differences may be attributed to genotypic variation, environmental factors, and the developmental stage of the fruit.

Maturity also plays a critical role in determining phenolic content. According to Tan et al. (2014), immature coconuts tend to have higher TPC than their mature and over-mature counterparts, highlighting the influence of physiological age on phenolic biosynthesis. Supporting this, Rios et al. (2020) found that green coconuts (9 months) contained 46.03 mg GAE/L, whereas mature coconuts (12 months) had 69.16 mg GAE/L, indicating variation not just with maturity, but also across studies and regions. Similarly, Mahayothee et al. (2016) demonstrated a decline in TPC from 7.08 mg GAE/100 mL at 190 days after pollination to 5.8 mg GAE/100 mL at 225 days, reinforcing the trend of decreasing phenolic levels with fruit maturity. Table 2 presents the phytochemical contents of coconut liquid endosperm (*Cocos nucifera* L.) as reported across various studies.

Table 2. Phytochemical contents of coconut liquid endosperm (*Cocos nucifera* L.) reported from various studies

Phytochemicals	Value	Variety	Maturity stage	References
Total phenolic content (Gallic acid equivalent)	6.04 mg/100 mL 9.07 mg/100 mL 7.67 mg/100 mL	Malayan tall Aromatic Dwarf coconut Hybrid coconut	5-6 month old	Asad et al., 2022
Flavonoid content (Quercetin equivalent)	100-150 mol/g 200-260 mol/g	Wenye No 5 Hainan local coconut	6 month old	Hou et al., 2024
Tannin content (Tannic acid equivalent)	10-30 µg/mL	Makapuno coconut	10 month-old	Phonphoem et al., 2022
Alkaloid content (Atropine equivalent)	2-5 µg/mL	Makapuno coconut	10 month-old	Phonphoem et al., 2022

Plant growth hormones

Phytohormones in coconut water play a crucial role in promoting plant growth and development, making coconut water a valuable natural supplement in tissue culture media. Most research studies have identified the presence of key plant growth regulators in coconut water, including auxins, cytokinins, gibberellins, and abscisic acid. Coconut water contains cytokinins such as zeatin and kinetin, which are known to stimulate cell division and shoot proliferation. In addition to cytokinins, several other plant growth regulators have been identified in coconut water. A study by Tan et al. (2014b), using capillary electrophoresis–tandem mass spectrometry (CE-MS), quantified the presence of indole-3-acetic acid (IAA), zeatin, gibberellic acid (GA), and abscisic acid (ABA) in immature coconut water. The concentrations reported were approximately 198.2×10^{-3} M IAA, 0.12×10^{-3} M zeatin, 49.6×10^{-3} M GA, and 15.3×10^{-3} M ABA. The CE-MS method utilised a cationic polymer-coated capillary to effectively distinguish these hormones (Ge et al., 2004).

A recent study by Amritha et al. 2023, investigated the composition and dynamics of plant growth regulators (PGRs) in the liquid endosperm of various coconut cultivars (West Coast Tall, Gangabondam) and their reciprocal hybrids (T×D and D×T) during seed development. Using LC-MS/MS analysis, the study quantified fifteen phytohormones from seven categories, including auxins (IAA, IBA), cytokinins (BA, tZ, tZR), gibberellins (GA_3, GA_4, GA_7), abscisic acid (ABA), jasmonates (JA, cis-JA, meJA), salicylic acid (SA), and brassinosteroids (24-epiBL). Among these, IAA, GA_4, BA, tZ, SA, jasmonates, and 24-epiBL were consistently present in higher concentrations across all genotypes. BA was more prominent in younger nuts (around four months), while mature nuts exhibited increased tZ levels. Salicylic acid was found in high concentrations at all developmental stages, indicating its crucial role in coconut seed physiology. IAA and SA were linked to key processes like solid endosperm formation and embryo differentiation. GA_4 levels increased towards maturity, while ABA remained low, possibly indicating quicker germination. Jasmonates were detected in considerable amounts across all cultivars, but te ethylene precursor ACC was minimal. Although the hormonal pattern was consistent across most cultivars and hybrids, notable variations were observed, especially in the Dwarf × Tall hybrid, which displayed distinct hormonal profiles. These findings highlight the role of genetic background in shaping PGR composition and behaviour in coconut seed development (Amritha et al., 2023)

However, there are relatively few comprehensive studies that quantitatively compare the levels of these hormones across different coconut varieties and stages of maturity. This limits a complete understanding of how varietal and developmental differences influence the hormonal profile of coconut water.

Physicochemical properties of coconut water

The physical and chemical characteristics of coconut water are influenced by a range of factors, including coconut variety, soil conditions, climate, and the maturity stage of the fruit. The volume and composition of coconut water vary with the stage of maturity. When the coconut reaches around 6–7 months of age, it typically contains the highest amount of water and sugars, contributing to its most desirable flavour. As the nut matures further (around 9–10 months), the water volume tends to decline due to the formation of jelly-like solid endosperm. Beyond 10 months, while the nut increases in size, its water-holding capacity may again rise depending on the variety (Jackson et al., 2004). Water yield also fluctuates seasonally: most varieties produce approximately 250–300 mL per nut during the dry season, which can increase to 400–500 mL in the wet season; some types can yield up to 750 mL.

The pH of coconut water also changes with maturation. Typically, the pH increases between seven and ten months as the nut matures, with a corresponding decrease in titratable acidity (Jackson et al., 2004). Organic acids such as malic, succinic, citric, acetic, and tartaric acids are indeed present in coconut water and contribute to its taste. These acids also influence the titratable acidity of the coconut water, which is a measure of the concentration of free acids in the liquid (Tuyekar et al., 2021). The pH range across all tested coconut water samples was between 4.68 and 5.27, indicating that coconut water is mildly acidic. Among the studied varieties, King coconut and CRIC 60 exhibited significantly higher pH values, whereas Brown dwarf showed a significantly lower pH. No statistically significant difference was observed between the pH values of Green dwarf and CRIC 65. This suggests that although variation exists, the pH of coconut water remains within a relatively narrow range across different varieties (Shayanthavi et al., 2024). Varieties with higher pH generally exhibit lower titratable acidity. The viscosity of coconut water is influenced by its total soluble solids (TSS) and water activity. As TSS levels increase, the viscosity tends to decrease, while water activity increases (Manjunatha and Raju, 2013).

Coconut water is considered a nutritious, natural beverage with a low energy value approximately 17.4 kcal per 100 g (Santos et al., 2013). It is known for its hydrating properties, subtle sweetness, and ability to support appetite regulation. At around 190 days after pollination, coconut water exhibits mild acidity and a pleasant sweetness. Coconut water can be classified based on maturity stages into immature (6–7 months), mature (10–11 months), and over-mature (12–13 months). Immature coconuts generally contain higher levels of total soluble solids. Over-mature coconuts, on the other hand, hold less nut water and are typically characterised by increased turbidity and a slightly salty taste (Tan et al., 2014a). Harvesting coconuts at the appropriate maturity stage is therefore critical for optimal water content and flavour, which tends to be sweet with a subtle sourness. Table 3 summarises the physicochemical characteristics of coconut liquid endosperm (*Cocos nucifera* L.) reported in various studies.

Table 3. Physicochemical characteristics of coconut liquid endosperm (*Cocos nucifera* L.) reported in various studies

Parameter	Value	Variety	Maturity stage	References
pH	4.73-5.01 5.48-5.74	Green dwarf	6-7 month old 8-9 month old	Kwiatkowski et al.,2008
Total Soluble Solids (TSS)	5.27-5.43 °Brix 5.23-6.13 °Brix	Green dwarf	6-7 month old 8-9 month old	Kwiatkowski et al.,2008
Titratable acidity	0.063 % 0.045 % 0.058 %	Malayan tall Aromatic Dwarf coconut Hybrid coconut	5-6 month old	Asad et al., 2022
Osmolarity	422.7 mOsm/L 419.6 mOsm/L	Dwarf coconut	6 month old 7 month old	Vigliar et al., 2006
Transmittance	95.22 (%T) 80.66 (%T)	Nam Hom coconut	6 month old 7-7.5 month old	Jirapong et al.,2015
Ash content	0.45-0.5 % 0.55-0.6 % 0.50-0.57 % 0.50-0.58 %	Yellow dwarf Orange dwarf Green dwarf Maypan	7-8 month old	Jackson et al., 2004

Antioxidant activity of coconut water

Coconut water possesses notable antioxidant properties that contribute to its growing recognition as a health-promoting natural beverage. These antioxidant effects are primarily due to the presence of bioactive compounds capable of neutralising free radicals and reducing oxidative stress in the body. Several in vitro assays have been used to evaluate the antioxidant potential of coconut water. Among the most widely applied are the DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging assay, oxygen radical absorbance capacity (ORAC), and ferric reducing antioxidant power (FRAP). These methods have consistently confirmed significant antiradical activity. For example, the Green Dwarf variety showed the highest DPPH scavenging capacity and lipid protection activity, correlating with its elevated phenolic and vitamin C content (Santos et al., 2013).

Coconut water has demonstrated the antioxidant capacity in DPPH, FRAP, and ABTS assays. For instance, fresh young coconut water exhibited the highest DPPH radical scavenging activity, reaching up to 60%. The Makapuno variety showed superior antioxidant activity in the ABTS assay (91% scavenging), compared to around 66% in mature and young coconut water. FRAP assay results similarly revealed strong reducing power in fresh Makapuno coconut water. Interestingly, freeze-drying led to more consistent antioxidant readings across samples, indicating the influence of sample processing (Phonphoem et al., 2022).

Key antioxidant compounds identified in coconut water include:

Flavonoids such as (+)-catechin and (–)-epicatechin, which stabilise reactive oxygen species (ROS) by donating electrons or hydrogen atoms (Prado et al., 2015). Vitamin C, which acts as a reducing agent, regenerates other antioxidants, and supports enzymatic antioxidant defences (Zulaikhah et al., 2021). L-arginine, an amino acid that stimulates the activity of endogenous antioxidant enzymes, especially superoxide dismutase (SOD), which detoxifies superoxide radicals.

Although coconut water mainly contains saturated fatty acids, some varieties also include unsaturated fatty acids such as oleic and linoleic acid, which are known to protect cell membranes and neutralise lipid peroxidation. Furthermore, aromatic and sulphur-containing amino acids may support antioxidant mechanisms by enhancing enzymatic activity and scavenging free radicals (Zhang et al., 2024).

The antioxidant potential of coconut water is also influenced by the maturity stage and varietal differences. Although total phenolic content (TPC) often decreases with maturity, antioxidant activity does not always follow this trend. In some cases, mature coconut water showed stronger DPPH scavenging activity, potentially due to the accumulation of other antioxidants such as vitamins, amino acids, and enzymes (Zhang et al., 2024). Moreover, hydroxyl radical scavenging activity was higher in water from younger coconuts (8–10 months), indicating that different antioxidant mechanisms may dominate at various developmental stages. Additionally, a study by Coulibaly et al. (2023) observed that antioxidant activity correlated strongly with condensed tannin content, while showing a negative correlation with total phenols and a weak negative correlation with flavonoids, suggesting that condensed tannins may play a prominent role in the antioxidant profile of some coconut varieties.

Antimicrobial properties of coconut water

Coconut water exhibits inherent antimicrobial properties, primarily due to a synergistic combination of bioactive peptides and phytochemical constituents. Among these, antimicrobial peptides (AMPs) play a central role in the innate defence mechanisms of the coconut. Three low-molecular-weight peptides, approximately 858 Da, 950 Da, and 1249 Da, have been isolated from green coconut water (*Cocos nucifera* L.) through reverse-phase high-performance liquid chromatography (HPLC). One of these, identified as Cn-AMP1, displayed potent antimicrobial activity against both Gram-positive and Gram-negative bacteria, suggesting the presence of naturally occurring defense agents with potential preservative properties (Mandal et al., 2009).

In addition to AMPs, phytochemical compounds, particularly lauric acid and its derivative monolaurin, contribute significantly to the antimicrobial potential of coconut water. These medium-chain fatty acids are well-documented for their ability to disrupt microbial cell membranes and interfere with critical cellular processes, ultimately inhibiting microbial growth (Yang et al., 2018). While lauric acid is generally more effective against Gram-positive bacteria, Gram-negative species tend to exhibit greater resistance (Anzaku et al., 2017). Moreover, the specificity of action is evident in studies where *Streptococcus mutans* was not inhibited by lauric acid, despite its proven activity against other organisms. This suggests a target-specific mechanism of activity (Rukmini et al., 2017).

Further reinforcing its antimicrobial potential, AMPs isolated from coconut water have shown efficacy against a range of human pathogenic microorganisms, supporting its use as a natural bio-preservative (Mandal et al., 2009). In the agricultural sector, mature coconut water was reported to inhibit the growth of *Pseudomonas fuscovaginae*, a pathogen responsible for brown rot disease in rice, highlighting its potential utility in plant disease management (Wahab et al., 2020).

Additionally, *Lactobacillus plantarum*, a probiotic strain isolated from fermented coconut water, exhibited strong antimicrobial effects against clinically significant pathogens such as *Salmonella typhi, Escherichia coli*, and *Staphylococcus aureus* (Prado et al., 2015). These findings suggest that both fresh and fermented forms of coconut water possess microbial inhibitory capabilities.

The antimicrobial activity of coconut water arises from a combination of peptides, medium-chain fatty acids, and other bioactive compounds. Its selective inhibitory effects, targeting pathogenic microorganisms while often sparing or promoting beneficial microbes, underscore its relevance as a natural and multifunctional antimicrobial agent with promising applications in food preservation and sustainable agriculture.

Utilizing Coconut water as a medium for microbial growth

Coconut water, particularly from young coconuts, contains a rich blend of nutrients that can support the growth of various microorganisms. To support optimal microbial development, the medium should provide essential nutrients, especially carbon and nitrogen, and remain free from any inhibitory substances. In addition to macronutrients, microorganisms require trace elements such as sulphur, phosphorus, and vitamins as micronutrients. Microorganisms, including bacteria, fungi, and yeasts, generally prefer simple sugars for growth and division, as many are unable to metabolise complex carbohydrates.

Traditionally, natural substrates like soya flour, meat extract, and barley have been used in microbial culture media (Mohua et al., 2009). Coconut water, with its balanced nutrient composition, has emerged as a promising alternative medium for microbial cultivation (Baretto et al., 2012).

Several studies have demonstrated the effectiveness of coconut water in supporting microbial growth. For example, Nurfujriani et al. (2020) reported that *Acetobacter xylinum* could utilise glucose in coconut water to synthesise cellulose. To enhance bacterial activity, coconut water was supplemented with urea (as a nitrogen source) and sucrose (as an additional carbon source). In a related study, Sari et al. (2021) explored optimised fermentation kinetics of *Acetobacter xylinum* FNCC 0001 by modifying glucose and peptone concentrations in a coconut water-based medium. These findings reinforce the potential of coconut water as a viable base for microbial media formulation.

Commercially available microbial media such as nutrient agar, potato dextrose agar, and MacConkey agar are often expensive and may not always be readily accessible. In this context, natural, locally available alternatives such as coconut water are of great interest. Prayekti et al. (2021) suggested that young coconut water could serve as a low-cost substitute for conventional basal media. Supporting this, Kapilan and Thavaranjit (2008) formulated a simple medium using 75 mL of coconut water, 25 mL of distilled water, and 6 g of sago. This combination supported the growth of both Gram-positive bacteria (*Bacillus, Enterococcus*) and Gram-negative bacteria (*Pseudomonas, Klebsiella, Serratia*) comparably to nutrient agar, with no significant differences in colony counts (Kapilan and Thavaranjit, 2008). Research on *Schizochytrium mangrovei* Sk-02 revealed that incorporating around 33% (v/v) of coconut water into a yeast extract–diluted seawater medium led to a marked improvement in biomass production and DHA (docosahexaenoic acid) yield. When coconut water was added to media containing different nitrogen sources such as peptone, tryptone, or casitone, it significantly boosted microbial growth and doubling the biomass levels. These findings indicate that coconut water can serve as an effective and economical growth medium component for cultivating certain microorganisms.

Further evidence from Sathiyavimal et al. (2014) indicated that coconut extract media can support the growth of *Mucor* sp., *Rhizobium* sp., *Klebsiella pneumoniae*, *Staphylococcus* sp., and *Streptococcus* sp. Similarly, Kuntiya et al. (2010) successfully used coconut water as a substitute for complex nitrogen sources in modified De Man, Rogosa and Sharpe (MRS) media for *Lactobacillus confusus.*

More recently, Evangelista et al. (2021) investigated the kinetic characterisation of *Morchella sp*. cultured in a medium comprising agar, malt extract, lactose, and 15% coconut water. The study found that the addition of coconut water not only promoted thick mycelial growth but also stimulated sclerotia formation, highlighting its utility in fungal cultivation.

Tender coconut water (TCW), due to its rich nutrient profile, has also been explored as a complete medium. Sekar et al. (2013) reported successful growth of *Escherichia coli* and *Pichia pastoris* in TCW. Although slight variability in growth outcomes may occur due to natural differences in the chemical composition among coconuts. Supplementing TCW with specific nutrients such as ammonium sulphate, amino acids, and magnesium sulphate has significantly improved microbial biomass, indicating that while TCW provides a strong nutrient base, certain additives can help standardise and enhance growth performance. These findings support the use of TCW as a promising, economical, and adaptable alternative to conventional microbial culture media (Sekar et al., 2013). Coconut water offers an innovative approach for cultivating microorganisms, providing both a sustainable and accessible option for various scientific and industrial applications.

Utilization of coconut water in tissue culture medium

Coconut water (CW) is widely employed in plant tissue culture due to its rich and diverse array of phytohormones, which can act as growth-promoting factors either individually or synergistically. It is commonly used at concentrations ranging from 2% to 20% (v/v), where it has been shown to enhance various developmental processes, such as callus formation, shoot multiplication, somatic embryogenesis, and organogenesis. Numerous studies have demonstrated the effectiveness of coconut water in promoting plant growth in vitro. In the tissue culture of *Ranunculus walliachianus*, different concentrations of CW (5%, 10%, and 20%) were tested in combination with growth regulators such as 6-benzyladenine (BA), kinetin, and thidiazuron (TDZ). The optimal result for shoot multiplication was achieved with 10% CW and 3 mg/L TDZ (Srinivasan et al., 2021).

In spinach (*Spinacia oleracea*) tissue culture, a medium supplemented with CW (alongside Murashige and Skoog basal salts, myo-inositol, thiamine-HCl, nicotinic acid, pyridoxine-HCl, 2-furanyl methyl-1-H-purine-6-amine, 2,4-D, and sucrose) led to a significant increase in callus fresh weight after four weeks. Media enriched with 10–15% CW produced more callus than CW-free media. However, there was no significant difference in shoot regeneration between CW-containing and CW-free conditions (Jameel et al., 1992). Sucrose, an essential carbon and energy source in tissue culture, supports cell division, and its effect is often enhanced when combined with CW. In *Dendrobium* ‘Gradita 31’, the proliferation of protocorm-like bodies was significantly stimulated by 15% CW in half-strength MS medium, whereas 30% CW adversely affected growth (Winarto et al., 2015).

Coconut water alone has also proven effective in shoot proliferation. In *Corylus avellana* L., CW significantly increased the number of shoots per explant. The most effective treatment combined 20% CW with 20 mg/L BA, 0.01 mg/L indole-3-acetic acid (IAA), and 0.5 mg/L gibberellic acid (GA3), which enhanced explant establishment (Prando et al., 2014). Similarly, in *Actinidia deliciosa* (kiwifruit), the highest number of nodes and maximum shoot length were observed with a medium supplemented with 20% CW and 2 mg/L BA (Nasib et al., 2008). In the microtuber formation of potato (*Solanum tuberosum*), the best results were obtained with 75 mL/L CW and 5 mg/L BA (Sembiring et al., 2020).

Other studies have shown the positive impact of CW on callus formation in sweet potato (*Ipomoea batatas*), where varying concentrations of CW promoted callus development from explants (Michael, 2011). In banana (*Musa* spp.) micropropagation, CW-enriched MS medium showed similar effectiveness to media containing 4.5 mg/L BA (Buah & Asare, 2014). Additionally, in date palm (*Phoenix dactylifera*) tissue culture, CW supplementation at 10–15% improved callus growth, somatic embryogenesis, and embryo germination (Khayri, 2015). These findings support the potential of CW as a cost-effective, natural alternative to synthetic growth regulators in plant tissue culture and micropropagation. However, as the effectiveness of CW varies by species and tissue type, it is vital to optimise its concentration for each plant system to ensure maximum efficacy.

Conclusion and future perspective

Tender coconut water (TCW) is a naturally sterile, nutrient-dense liquid endosperm enriched with essential minerals, sugars, amino acids, vitamins, and bioactive compounds such as polyphenols, flavonoids, and antioxidants. Its composition is significantly influenced by factors such as variety, maturity stage, and environmental conditions. These phytochemical and nutritional properties contribute to its functional value and underline its potential in diverse biotechnological applications.

In plant tissue culture, TCW has demonstrated its ability to support callus initiation, shoot regeneration, and somatic embryogenesis due to the presence of naturally occurring cytokinins and auxin-like substances. However, its inconsistent composition, lack of essential macro- and micronutrients, and variability among coconut limit its use as a complete medium. Standardisation of its concentration, sterilisation methods, and supplementation protocols is essential to ensure reproducibility across different species and experimental systems.

In microbial biotechnology, TCW has been evaluated as a cost-effective substrate and a source of growth-promoting and antimicrobial compounds. While some studies report its effectiveness in supporting microbial growth or inhibiting pathogenic strains, comprehensive investigations are still needed to determine its selective properties, optimal formulations, and efficacy against a wider range of organisms.

Preservation of TCW remains a critical challenge due to its susceptibility to microbial spoilage and enzymatic degradation. Traditional thermal treatments often compromise its sensory and nutritional qualities. Therefore, non-thermal preservation technologies such as ultraviolet irradiation, high-pressure processing, and sonication are gaining interest for retaining its freshness and functional integrity during storage and distribution.

Future research should prioritise detailed profiling of coconut water bioactive components and elucidate their specific roles in plant and microbial systems. Investigations into its influence on plant acclimatisation, stress tolerance, and post-transplant development could offer valuable insights for sustainable agriculture. Moreover, its integration into low-cost culture media formulations could reduce dependency on expensive synthetic ingredients. For successful commercialisation, consistent sourcing, processing, and quality control protocols must be developed. Scalable preservation methods and regulatory guidelines are also needed to support its industrial application in functional beverages, microbial media, and tissue culture systems.

Liquid endosperm of coconut is a promising, multifunctional natural resource with broad applicability across biotechnology and agriculture. With targeted research and systematic optimisation, it holds strong potential for practical deployment and commercial exploitation in sustainable, nature-based innovations.

Conflicts of interest

The authors declare that they have no conflict of interest.

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