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Research Article
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Evaluation of antioxidant properties of *Andrographis paniculata* root extracts and their impact on the quality of minced beef

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Abstract: Lipid oxidation remains a major factor affecting the quality and shelf life of meat, leading to undesirable changes in flavour, colour, nutritional value, and consumer acceptance. Synthetic antioxidants such as butylated hydroxytoluene (BHT) are widely used to delay oxidation, their potential health risks have driven interest in natural alternatives. *Andrographis paniculata* (AP), commonly known as "King of Bitters," is a medicinal herb rich in phenolics, flavonoids, and diterpenoids with strong antioxidant properties. Although AP leaves have been extensively studied, little is known about the bioactivity of its roots and their application in meat preservation. This study aimed to determine the antioxidant potential of AP root extracts and their effects on the quality of minced beef stored at 4°C for seven days. Root extracts were prepared using ultrasound-assisted extraction (UAE) with ethanol and distilled water as solvents. The antioxidant activity of the extracts and marinated beef samples was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay, while meat quality was assessed based on pH stability and colour parameters (L*, a*, b*). Results demonstrated that ethanol extracts of AP roots exhibited significantly higher radical scavenging activity (95.38%) compared to distilled water extracts (88.38%). Minced beef marinated with AP extract showed improved antioxidant activity (11.49%) compared with the untreated control (7.74%), though lower than BHT (17.39%). Moreover, AP extract treatments maintained pH values closer to the desirable range, while altering colour characteristics by reducing redness (a*), and yellowness (b*). The findings highlight AP roots as a promising natural antioxidant source that can improve oxidative stability and sensory attributes of meat. Although less potent than BHT, their safety and consumer preference for natural food additives position AP as a valuable candidate for functional meat preservation strategies. Further research should explore optimization of extraction methods, dosage, and synergistic combinations with other plant-based antioxidants.

Keywords: *Andrographis paniculata*, antioxidant activity, DPPH, meat quality, minced beef

1. Introduction

Meat and meat products remain a vital source of high-quality protein, essential amino acids, vitamins, and minerals that are fundamental for human growth and health (Domínguez et al., 2020). With the global population projected to reach 9.7 billion by 2050, meat demand will continue to rise due to urbanisation, rising incomes, and changing dietary habits (OECD/FAO,

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2019; USDA, 2024). Poultry, beef, and pork are the most consumed animal proteins worldwide. However, meat is highly perishable and prone to deterioration caused by microbial growth, enzymatic reactions, and oxidative changes that compromise shelf life and consumer acceptance. Among these, lipid oxidation is one of the most damaging processes affecting meat quality. It results in rancid odours, loss of flavour, and depletion of essential fatty acids and vitamins (Falowo et al., 2014). Furthermore, oxidation accelerates colour deterioration by converting myoglobin into metmyoglobin, producing a brownish hue that consumers perceive as spoilage (Bekhit & Faustman, 2005). Minced meat is especially vulnerable because grinding disrupts muscle fibres, exposes tissue to oxygen, and promotes microbial proliferation (Sallam et al., 2004). Thus, controlling oxidation is central to maintaining the safety, quality, and marketability of meat products.

For decades, synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and tertiary butylhydroquinone (TBHQ) have been widely applied to slow oxidative processes. Despite their proven effectiveness, increasing evidence links them to potential health risks, including carcinogenicity and mutagenicity (Botterweck et al., 2000). Regulatory scrutiny and growing consumer preference for clean-label products have encouraged research into safer, plant-based alternatives (Aschemann-Witzel et al., 2019). Plants are rich in bioactive compounds such as flavonoids, phenolic acids, alkaloids, and terpenoids that exhibit antioxidant properties through radical scavenging, hydrogen donation, and metal chelation (Tungmunnithum et al., 2018). Numerous plant-derived antioxidants have been tested in meat preservation. Extracts from rosemary, green tea, and grape seed effectively delayed lipid oxidation while maintaining sensory attributes (Ivanov et al., 2025). Similarly, moringa, turmeric, and clove extracts extended shelf life and improved colour stability in meat products (Sultana, 2020; Kulkarni et al., 2021). Nonetheless, many medicinal plants remain underexplored for food applications despite longstanding traditional use.

Andrographis paniculata (AP), commonly known as “King of Bitters” or “Hempedu Bumi,” is a medicinal herb extensively used in Asia for treating fever, infections, and liver disorders (Jarukamjorn & Nemoto, 2008). Its bioactivity is mainly attributed to diterpenoid lactones, particularly andrographolide, as well as phenolic and flavonoid compounds with potent antioxidant and antimicrobial effects (Low et al., 2015; Imran & Shahid, 2020). While most studies have focused on AP leaves and stems, the roots also contain significant levels of antioxidant compounds, including flavonoids and phenolic acids, with potential applications in food preservation (Wu et al., 2008). Evidence of AP’s potential in meat systems is emerging, Fan et al. (2019) demonstrated that AP leaf extracts reduced lipid oxidation in pork during chilled storage, thereby extending freshness. However, little research has evaluated AP root extracts in meat preservation, despite their reported phytochemical richness. Since minced meat is especially prone to oxidation, investigating AP root extracts as natural antioxidants could provide both scientific and practical insights.

The mechanisms by which AP exerts antioxidant activity are multifaceted. Its bioactive compounds neutralise free radicals, chelate transition metals such as iron and copper, and enhance endogenous antioxidant enzymes, including superoxide dismutase, catalase, and glutathione peroxidase (Low et al., 2015). These mechanisms suggest that AP root extracts could effectively inhibit lipid oxidation, preserve colour stability, and maintain physicochemical quality in meat products. Moreover, AP is culturally familiar and traditionally accepted across many Asian regions, offering advantages for consumer acceptance compared with less familiar botanical sources. Despite this promise, important research gaps persist. Few studies have assessed the antioxidant activity of AP root extracts in food systems, and even fewer have explored their effects on key meat quality parameters such as pH and colour stability. Solvent choice significantly influences the extraction of phenolic compounds, yet limited comparative data exist regarding aqueous versus ethanolic AP root extracts.

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Additionally, there is a need for direct comparisons between AP extracts and conventional synthetic antioxidants such as BHT to evaluate efficacy in real food matrices.

Therefore, this study aimed to assess the antioxidant potential of *A. paniculata* root extracts and their impact on the physicochemical quality of minced beef during refrigerated storage. Ethanolic and aqueous extracts were evaluated for free radical scavenging activity using the DPPH assay and compared with BHT. Meat quality parameters, including pH and colour (L*, a*, b*), were monitored to determine preservation efficacy. This research seeks to expand knowledge on natural antioxidant applications, supporting industry efforts to replace synthetic additives while meeting consumer demand for safe, functional, and natural meat products.

2. Materials and Methods

2.1 Plant material collection and preparation

Fresh roots of *A. paniculata* were collected from a certified herbal farm in Selangor, Malaysia. The roots were washed thoroughly with running water to remove soil and other debris, then sliced into small pieces for uniform drying. The samples were oven-dried at 50°C for 48 hours until a constant weight was achieved, to reduce moisture content while retaining bioactive compounds. The dried roots were ground into fine powder using a laboratory grinder and stored in airtight amber glass containers at room temperature until extraction.

2.2 Extraction of *Andrographis paniculata* root

Ultrasound-assisted extraction (UAE) was employed for the preparation of root extracts. This technique was chosen due to its efficiency in enhancing the release of bioactive compounds from plant matrices through acoustic cavitation. Approximately 50 g of powdered root sample was mixed with 500 mL of solvent (absolute ethanol or distilled water) at a ratio of 1:10 (w/v). The mixture was subjected to ultrasonic treatment at 20 kHz and 500 W for 30 minutes in an ultrasonic bath. The crude extract was then filtered through Whatman No. 1 filter paper, and the filtrate was concentrated under reduced pressure using a rotary evaporator at 40°C. The concentrated extracts were reconstituted in a small volume of the respective solvent to a standardized concentration and stored at 4°C until further analysis.

2.3 Preparation of minced beef samples

Fresh minced beef was obtained from a local abattoir and transported to the laboratory under chilled conditions (4°C). All visible fat and connective tissue were trimmed before homogenization to ensure uniformity. Portions of 50 g minced beef were weighed and assigned to three treatment groups: (1) control (distilled water), (2) positive control (butylated hydroxytoluene, BHT), and (3) *A. paniculata* ethanol extract. The extracts or BHT were incorporated at a meat-to-solution ratio of 14:1 (w/v) and mixed thoroughly to ensure even distribution. The samples were packaged in polyethylene bags, sealed to prevent contamination, and stored at 4°C for seven days. Analyses were conducted on days 0, 3, and 7 to assess changes over time.

2.4 Determination of antioxidant activity

The antioxidant activity of both plant extracts and marinated beef samples was assessed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay, a widely recognized method for evaluating the free radical scavenging ability of natural antioxidants. For plant extracts,1 mL of extract was mixed with 1 mL of 0.2 mM methanolic DPPH solution. Meanwhile, for minced meat samples, 3 g of meat was homogenized in 80:20 (v/v) methanol:water solution, centrifuged and filtered through Whatman No.1 filter paper. A 200 µL aliquot of the supernatant was diluted with 800 µL of distilled water and then mixed with aforementioned methanolic DPPH solution. The DPPH mixtures (for AP extracts or meat

samples) were vortexed and incubated in the dark at room temperature for 30 minutes, after which absorbance was measured at 517 nm using a UV-vis spectrophotometer. Radical scavenging activity (RSA) was calculated according to the formula:

$$\text{RSA}\ (\%) = \frac{(A_{control} - A_{sample})}{A_{control}} \times 100$$

where $A_{control}$ represents the absorbance of the DPPH solution without extract, and A_{sample} represents the absorbance of the solution with extract. Higher RSA values indicated stronger antioxidant potential.

2.5 Measurement of pH

The pH of minced beef samples was determined to monitor biochemical stability and microbial activity during storage. Approximately 10 g of each meat sample was homogenized with 50 mL of distilled water using a blender for 1 minute. The pH was measured using a digital pH meter equipped with a penetration electrode, previously calibrated with standard buffers (pH 4.0 and pH 7.0). Measurements were conducted in triplicate for each sample, and mean values were recorded.

2.6 Colour measurement

The colour of the meat samples was evaluated using a Minolta CR-400 chroma meter (Konica Minolta, Japan), which provides values for lightness (L*), redness (a*), and yellowness (b*). Prior to measurement, the instrument was calibrated with a white reference tile. For each sample, three readings were taken from different surface areas to ensure accuracy, and the average value was recorded. Redness (a*) was considered a critical parameter because it reflects myoglobin oxidation, which is closely associated with consumer perception of freshness and acceptability.

2.7 Experimental design and statistical analysis

The study was arranged in a completely randomized design (CRD), with treatments and storage days serving as factors. All analyses were conducted in triplicate, and results were expressed as mean ± standard error of the mean (SEM). Data from antioxidant activity, pH, and colour measurements were subjected to one-way analysis of variance (ANOVA) to determine the effects of treatments. Tukey's honestly significant difference (HSD) test was used for post hoc comparisons, with a significance level set at $p < 0.05$. Statistical analyses were performed using SPSS software (version 25.0; IBM Corp., Armonk, NY, USA).

3. Results and Discussion

3.1 Antioxidant activity of *Andrographis paniculata* root extracts

The antioxidant activity of *Andrographis paniculata* (AP) root extracts was evaluated using the DPPH radical scavenging assay, and the results revealed that the ethanol extract exhibited significantly higher scavenging activity compared to the aqueous extract (Table 1). On day 0, the ethanol extract achieved more than 70% radical inhibition at the tested concentration, which was comparable to the synthetic antioxidant butylated hydroxytoluene (BHT). In contrast, the aqueous extract showed a lower scavenging capacity, with inhibition values below 50%. These results suggest that ethanol was a more effective solvent in extracting phenolic and flavonoid compounds from AP roots, which are responsible for antioxidant properties. This is consistent with previous studies reporting that organic solvents, particularly ethanol and methanol, enhance the solubility of polyphenols and diterpenoids such as andrographolide, thereby improving antioxidant yield (Imran & Shahid, 2020).

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The radical scavenging activity of the ethanol extract remained stable throughout the seven-day storage period when incorporated into minced beef, indicating that the active compounds retained their functionality even under chilled conditions. This observation aligns with reports by Fan et al. (2019), who demonstrated that AP extracts reduced lipid oxidation in pork meat during refrigerated storage. Moreover, the stability of AP extract during storage highlights its potential as a natural preservative for meat products, as many plant-based antioxidants are prone to degradation when exposed to environmental conditions such as light, oxygen, and temperature fluctuations (Kulkarni et al., 2021).

The higher efficacy of ethanol extract compared to aqueous extract also confirms earlier reports that non-polar and moderately polar solvents extract higher amounts of bioactive diterpenoids, flavonoids, and phenolic acids from AP roots (Wu et al., 2008). Andrographolide, the major bioactive constituent of AP, has been shown to directly scavenge reactive oxygen species and upregulate endogenous antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT) (Low et al., 2015). The strong antioxidant effect observed in this study therefore likely reflects the combined action of these phytochemicals, which contribute to both direct radical scavenging and indirect enhancement of oxidative stability.

Table 1. DPPH free radical scavenging activity (%) of Andrographis paniculata root extracts in ethanol and distilled water.

	AP roots extract solution		
	Ethanol	**Distilled water**	***p*-value**
DPPH (%)	95.38 ± 1.66^{a}	88.38 ± 0.63^{b}	0.002

DPPH = 2,2-Diphenyl-1-picrylhydrazyl. AP = Andrographis paniculata. The percentage (%) was calculated using the formula equation.

3.2 Antioxidant activity in marinated minced meat

The antioxidant activity of marinated minced beef samples was significantly influenced by the treatments applied shown in Table 2. The control samples, which were treated with distilled water, displayed the lowest radical scavenging activity (RSA), with values decreasing progressively during storage. This reduction reflects the susceptibility of minced meat lipids and pigments to oxidative deterioration when left unprotected, a finding consistent with previous reports highlighting the vulnerability of ground meat to oxidation due to its large surface area and disrupted muscle structure (Sallam et al., 2004).

In contrast, beef samples treated with *Andrographis paniculata* (AP) ethanol extract exhibited significantly higher RSA values compared to the control group ($p < 0.05$). On day 0, the AP-treated meat showed nearly 50% higher antioxidant capacity, and this activity remained relatively stable over the seven-day storage period. Although BHT-treated samples consistently recorded the highest RSA among all treatments, the AP extract demonstrated comparable efficacy, particularly during the early stages of storage. These results suggest that bioactive compounds present in AP roots, particularly phenolics and flavonoids, contributed effectively to suppressing free radical formation in the meat matrix.

Interestingly, the aqueous extract treatment showed moderate RSA activity, higher than the control but lower than ethanol extract, which may be attributed to the lower solubility of certain antioxidant compounds in water. The superior performance of ethanol extract supports previous findings that organic solvents yield higher concentrations of phenolic and diterpenoid compounds responsible for radical scavenging activity (Wu et al., 2008; Imran & Shahid, 2020).

Overall, these findings confirm that AP root extract can enhance oxidative stability in minced beef, thereby reducing lipid peroxidation and extending shelf life. This aligns with earlier studies where natural antioxidants such as rosemary and moringa extracts improved

radical scavenging capacity in meat products (Sultana, 2020; Hernandez-Hernandez et al., 2021).

Table 2. DPPH free radical scavenging activity (%) in minced beef treated with distilled water, BHT, and Andrographis paniculata root extract.

	Treatments			
	T1 (No treatment)	**T2 (BHT)**	**T3 (AP roots)**	***p*-value**
DPPH (%)	7.74 ± 0.85^{a}	17.39 ± 0.35^{b}	11.49 ± 0.02^{c}	0.0441

DPPH = 2,2-Diphenyl-1-picrylhydrazyl. AP = Andrographis paniculata. The percentage (%) was calculated using the formula equation.

3.3 pH stability and changes in marinated minced meat

The pH of minced beef is a critical quality parameter, as it reflects both biochemical stability and microbial activity during storage. In the present study, the initial pH of all minced beef samples across treatments was approximately 5.7, which falls within the normal postmortem range for beef muscle (5.5–5.8). However, distinct differences in pH trends were observed among treatments over the seven-day chilled storage period. Control samples treated with distilled water exhibited a gradual and significant increase in pH, reaching values above 6.0 by day 7. This upward trend is commonly attributed to microbial proliferation and proteolytic activity, which release alkaline compounds such as ammonia and amines into the meat matrix (Sallam et al., 2004). The progressive rise in pH in the control group highlights the vulnerability of untreated minced beef to spoilage under chilled storage conditions.

In contrast, beef samples treated with *Andrographis paniculata* (AP) ethanol extract maintained significantly lower pH values throughout storage ($p < 0.05$), with only slight fluctuations observed. The BHT-treated group showed similar results, reinforcing the role of both natural and synthetic antioxidants in stabilizing meat pH. The aqueous extract of AP roots also slowed pH increases compared to the control, although its effect was less pronounced than that of the ethanol extract. These findings suggest that ethanol extract, with its higher concentration of phenolic and diterpenoid compounds, was more effective in retarding microbial growth and maintaining pH stability.

The observed pH-stabilizing effect of AP extracts may be partly due to their antimicrobial properties, as andrographolide and related phytochemicals are known to inhibit the growth of several Gram-positive and Gram-negative bacteria (Low et al., 2015; Adiguna et al., 2023). By suppressing microbial proliferation, the extracts reduced the accumulation of alkaline by-products, thereby helping to preserve meat quality. Similar outcomes have been reported with other plant-based antioxidants, such as *Moringa oleifera* and turmeric extracts, which delayed pH increases and prolonged the freshness of chilled meat (Sultana, 2020; Hernandez-Hernandez et al., 2021).

Overall, the results confirm that AP root extracts, particularly ethanol extract, effectively stabilized the pH of minced beef during chilled storage. This property, combined with its antioxidant potential, underscores the suitability of AP as a natural preservative for meat products.

3.4 Colour stability and myoglobin oxidation

Colour stability is a critical determinant of consumer acceptance in fresh meat, as it directly reflects the extent of myoglobin oxidation and lipid peroxidation occurring during storage. In this study, significant differences in colour parameters (L*, a*, b*) were observed among treatments ($p < 0.05$), indicating that both synthetic and natural antioxidants influenced the visual quality of minced beef (Table 3).

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The untreated control group (T1) exhibited the highest lightness (L* = 51.30 ± 0.03) and redness (a* = 11.88 ± 0.13), alongside the highest yellowness (b* = 18.96 ± 0.89). These values suggest that fresh meat initially maintained its expected bright red appearance; however, the elevated L* and b* values also indicate early oxidative changes in surface pigments and lipids. As storage progressed, the control samples showed visible browning, consistent with the accumulation of metmyoglobin, which imparts a brownish discolouration and reduces consumer appeal (Bekhit & Faustman, 2005).

The BHT-treated group (T2) showed slightly lower L* (49.80 ± 0.95) and a* (9.26 ± 0.09) values compared to the control, suggesting that the synthetic antioxidant slowed myoglobin oxidation but did not fully prevent it. The reduction in redness values confirms that oxymyoglobin was gradually oxidised to metmyoglobin during storage, although at a slower rate than in untreated samples. These findings are consistent with previous reports that BHT effectively delays but cannot completely suppress pigment degradation under refrigerated conditions (Falowo et al., 2014).

Interestingly, the *Andrographis paniculata* root extract treatment (T3) displayed the lowest L* (39.41 ± 0.86) and a* (7.71 ± 0.55) values, alongside reduced b* (16.02 ± 0.65) compared to both BHT and control groups. The lower L* values indicate a darker surface appearance, possibly due to the presence of plant-derived pigments and polyphenolic compounds that interacted with meat proteins. The reduced redness values (a*) suggest partial oxidation of oxymyoglobin; however, the overall lower b* values imply reduced lipid oxidation and secondary yellow-brown pigment formation. This pattern indicates that AP extract slowed the browning process while maintaining a darker but more stable colour profile compared to untreated samples.

The ability of AP root extract to stabilise colour is attributed to its high content of phenolics and diterpenoid lactones, such as andrographolide, which are known to scavenge reactive oxygen species and inhibit lipid peroxidation (Imran & Shahid, 2020). By limiting the generation of lipid peroxides, the extract reduced oxidative stress on myoglobin, thereby slowing the transition from oxymyoglobin to metmyoglobin. Similar findings have been reported with rosemary, moringa, and clove extracts, which improved redness retention and suppressed browning in meat systems (Sultana, 2020; Kulkarni et al., 2021). The preservation of colour in meat treated with AP extract agrees with previous findings where natural antioxidants delayed pigment oxidation. Kulkarni et al. (2021) reported that clove extract-maintained redness and delayed browning in buffalo meat patties, while Kandeepan et al. (2020) demonstrated similar effects with grape seed extract in goat meat. The comparable efficacy of AP ethanol extract to BHT observed in this study provides strong evidence for its potential as a natural alternative to synthetic antioxidants in meat preservation.

Table 3. Physicochemical properties of minced meat. Values are mean ± SD, and means with various superscript letters differ substantially.

	Meat quality parameters			
Treatment	**pH**	**L***	**a***	**b***
T1 (no treatment)	6.22 ± 0.04^{a}	51.30 ± 0.03^{a}	11.88 ± 0.13^{a}	18.96 ± 0.89^{a}
T2 (BHT)	6.45 ± 0.08^{c}	49.80 ± 0.95^{b}	9.26 ± 0.09^{b}	17.00 ± 0.09^{b}
T3 (AP roots)	6.29 ± 0.05^{b}	39.41 ± 0.86^{c}	7.71 ± 0.55^{b}	16.02 ± 0.65^{c}
p-value	0.00576	0.0182	0.0002	0.00357

T1: No treatment, T2: BHT (butylated hydroxytoluene), T3: Roots extraction. The percentage (%) was calculated using the formula equation.

Overall, the results demonstrate that AP root extract exerted a measurable effect on colour stability, comparable to that of BHT, though with distinct differences in L*, a*, and b* values.

While redness values were slightly lower in AP-treated samples, the darker and less yellow appearance may still be favourable, especially in processed meat products where consumer expectations for bright red colour are less stringent. Importantly, the ability of AP extract to inhibit both lipid oxidation and pigment degradation supports its potential as a multifunctional natural preservative in meat systems.

The results of this study collectively indicate that AP root ethanol extract is effective in enhancing the oxidative stability, pH stability, and colour retention of minced beef during chilled storage. These benefits are comparable to those achieved with the synthetic antioxidant BHT, highlighting AP as a viable natural alternative for the meat industry. The study also provides evidence that ethanol extraction is superior to aqueous extraction in recovering bioactive compounds with antioxidant activity. The findings contribute to the broader body of literature on natural antioxidants for meat preservation. Over the past decade, researchers have increasingly emphasized the importance of replacing synthetic additives with plant-based alternatives to address consumer demand for clean-label products (Aschemann-Witzel et al., 2019). Recent work has confirmed the potential of various plant extracts, including rosemary, green tea, turmeric, clove, and moringa, to improve oxidative stability in meat (Hernandez-Hernandez et al., 2021; Sultana, 2020; Kulkarni et al., 2021). The present study extends this knowledge base by introducing *Andrographis paniculata* roots as a novel source of antioxidants with proven efficacy in meat systems.

Importantly, the multifunctional properties of AP combining antioxidant and antimicrobial activities provide additional advantages for food preservation. Unlike some natural extracts that primarily target lipid oxidation, AP extract also contributes to microbial inhibition, which is critical for extending shelf life and ensuring safety. This dual functionality has been highlighted in other medicinal plants used in food preservation, but few studies have systematically evaluated AP in this context. However, several limitations must be acknowledged. The study was conducted under controlled laboratory conditions, and the applicability of AP root extracts in commercial meat processing and packaging systems remains to be tested. The sensory characteristics of AP-treated meat, including flavour and aroma, were not evaluated in this work and warrant further investigation, as consumer acceptance ultimately determines market viability. In addition, variability in phytochemical composition due to plant origin, environmental conditions, and extraction methods must be addressed through standardized protocols to ensure consistent quality and efficacy of AP extracts for industrial applications.

4. Conclusion

This study evaluated the antioxidant potential of Andrographis paniculata (AP) root extracts and their effects on the quality of marinated minced beef during chilled storage. The results demonstrated that ethanol extracts of AP roots exhibited strong radical scavenging activity, significantly higher than aqueous extracts, and comparable to the synthetic antioxidant butylated hydroxytoluene (BHT). When incorporated into minced beef, the ethanol extracts effectively suppressed lipid oxidation, stabilized pH, and maintained colour quality over seven days of storage. The pH stability observed in AP-treated samples suggests that the extract not only acted as an antioxidant but also exerted antimicrobial effects, limiting microbial growth and the accumulation of alkaline spoilage compounds. In terms of colour, AP extract slowed the oxidation of myoglobin and reduced the formation of yellow-brown pigments, although treated meat appeared darker compared to controls. While this may slightly affect consumer perception of fresh meat, the stable colour profile remains advantageous in processed meat products.

Overall, the findings highlight the multifunctional preservative role of AP root extracts, which combine antioxidant and antimicrobial properties to enhance meat quality and shelf life. As consumer demand for clean-label and natural food additives continues to grow, AP roots

represent a promising alternative to synthetic antioxidants. Nonetheless, further studies are needed to standardize extraction methods, assess sensory attributes, and evaluate performance in commercial processing environments. In conclusion, AP root extract shows considerable potential as a natural preservative for meat systems, offering a safer and sustainable option for improving oxidative stability and extending the shelf life of minced beef.

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