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Polycyclic aromatic hydrocarbon mitigation and potential physicochemical consequences of plant-based wrappings in grilled beef and camel steak

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ABSTRACT

Further research is necessary to establish a cost-effective mitigation strategy for carcinogenic and mutagenic polycyclic aromatic hydrocarbons (PAHs) generated during grilling. This study aims to evaluate the impact of naturally occurring plant-based wrappings, specifically *Phoenix dactylifera fronds* (PDF) and *Leptadenia pyrotechnica* (LP), on the generation of polycyclic aromatic hydrocarbons (PAHs) in beef (*BSMTS*) and camel (*CSMTS*) Musculus *semimembranosus* and *semitendinosus* steaks. The influence of meat species and physicochemical variables on PAH generation was also examined. The physicochemical properties of BSMTS and CSMTS, including water-holding capacity and purge loss, did not exhibit significant differences. Furthermore, grilled *BSMTS* and *CSMTS* exhibited no significant variation in cooking loss. Only one distinction in pHU was seen, with camel exhibiting a higher pH than beef ($P < 0.05$). Moreover, *PDF* or *LP* wrappings diminished cooking loss in BSMTS and *CSMTS* compared to the control group ($P > 0.05$). Statistically, control camel meat exhibited more Warner-Bratzler shear force (WBSF) compared to beef. In comparison to the control, the application of *LP* or *PDF* to *CSMTS* and *BSMTS* significantly diminished WBSF ($P < 0.05$). The amounts of PAH4 and benzo[a]pyrene (B[a]P) were greater in camel *SMTS* than in *BSMTS* ($P < 0.05$). The significance of grilling times as a PAH mitigation strategy was confirmed by the fact that all groups had violative levels of PAH indices. BSMTS and CSMTS wrapped with *LP* had the lowest amounts of benzo[a]pyrene (B[a]P) and PAH4. Ultimately, plant-wrapping reduced PAHs relative to the control, although its effectiveness in preventing violation is time-dependent.

1. INTRODUCTION

Cooking aims to yield bacteriologically safe food with optimal sensory qualities and minimal hazardous ingredients; nevertheless, research indicates that elevated cooking and food processing temperatures can generate various genotoxic compounds, commonly known as cooking toxicants.

Multiple organizations assessed and classified the most significant and hazardous PAHs. The 2005 European Commission Recommendation and the EFSA Panel on Contaminants in the Food Chain (CONTAM) identified B[a]P as an inadequate indication of other PAHs in food products (European Commission, 2005; World Health Organization, 2005). The cumulative concentration of the four heavy PAHs (benzo[a]pyrene, chrysene, benzo[b]fluoranthene, and benzo[a]anthracene) has been recognized as the most reliable indicator of PAH presence in food (European Food Safety Authority (EFSA), 2008).

In 2010, the International Agency for Research on Cancer (IARC) further classified polyarenes into four groups based on their carcinogenicity: group 1 was classified as human carcinogens, group 2A as probable carcinogens, group 2B as possible carcinogens, group 3 as not classifiable as human carcinogens, and group 4 as probably not carcinogenic to humans (International Agency for Research on Cancer, 2010). In 2022, there were 19,976,499 occurrences of all cancers across both genders, with an expected 1,185,216 cases (5.9%) reported in Africa. The largest prevalence occurred in Egypt, with approximately 150,578 cases (12.7%) of all malignancies, followed by Nigeria (127,763 cases, 10.8%) (Wéber et al., 2024).

Various thermo-processing techniques, such as smoking, grilling, barbecuing, roasting, and frying, which employ hot fuels and elevated temperatures, generate PAHs in processed meat (Das et al., 2023). Foods exhibiting decreased scavenging capacity were correlated with elevated PAH levels. Prior studies indicated that free radical chains function as a mediator in the synthesis of polycyclic aromatic hydrocarbons (García-Lomillo et al., 2017).

To reduce human exposure to PAHs and their detrimental health consequences, it is essential to implement effective methods utilizing diverse food processing techniques to prevent and mitigate contamination (Nowar et al., 2025; Sampaio et al., 2021). Our latest study revealed that encasing beef and camel *longissimus lumborum* steaks (BSMTS vs. CSMTS) in aluminum foil significantly lowered benzo[a]pyrene and PAH4 concentrations beneath the permissible limits. PAH concentrations were elevated in CSMTS relative to BSMTS ($P < 0.05$) (Nowar et al., 2025). Meat wrapping is one of the approaches offered for preventing and limiting contamination. Thus, the focus has transitioned to the utilization of naturally available plant-based coverings.

Forssk, or *Leptadenia pyrotechnica* (*L. pyrotechnica, LP*), is a wild plant that grows primarily in the Mediterranean region in semi-arid deserts. The *LP* plant is commonly referred to as "Markh" in the Arabian Peninsula, meaning "soft and flexible plant" (Ali, 2001). Remarkably, *LP* is

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used in the Middle East, particularly in the Gulf region, to improve the flavor of portions of lamb meat while it is cooking. In the Middle East, this plant is also grown on streets, farms, and forests for its health advantages (Preet, 2018).

A potential natural wrapping material is palm fronds, particularly those from the date palm (Phoenix dactylifera). Date leaves and subsequently "date seeds" are garnering scientific interest as a significant waste resource due to their richness in several bioactive and functional chemicals, including dietary fibers and phenolics, and the lignocellulosic material they possess (Ahmad et al., 2021). The predominant emphasis of most research on functional food development from date by-products is on DPS valorization, while other components, such as date leaves, are hardly considered (Manai et al., 2024).

These results (Nowar et al., 2025) consequently contributed to the current study's goal of evaluating the effects of naturally occurring plant-based wrapping, like the fronds of *Phoenix dactylifera* and *Leptadenia pyrotechnica*, on the production of PAHs. The impact of meat species and associated physicochemical characteristics on the formation of PAHs was also investigated in beef and camel meat. Furthermore, the paper's positive findings will also serve as a basis for future research.

2. MATERIAL AND METHODS

Experiment management and approval.

The methods employed in this work were authorized by the Institutional Animal Care and Use Committee Research Ethics number (BUFVTM) of Benha University's Faculty of Veterinary Medicine, with the number BUFVM 35-12-2024.

Plant preparation.

On the day of the grill, Phoenix dactylifera fronds (CPDF, BPDF, and W/W) were collected from a date palm tree (Native Zaghloul variety) at Benha University's Faculty of Agriculture in Egypt. *Leptadenia pyrotechnica* was procured from the southern part of Saudi Arabia and thereafter stored at -21°C until the day of grilling. To encase beef steaks in aluminium foil and cover them with 10% of the examined plant and leaf, the plants were chopped.

Top/eye round steaks preparation and wrapping

Top and eye round steaks (*Musculus semimembranosus and* semitendinosus, *SMTS*) were obtained 24 hours post-mortem from two young beef (BSMTS) and two young camel (CSMTS) carcasses sourced from a local butcher. The samples were immediately transported under chilled conditions to the laboratory for further analysis. From both sides of each carcass, SMTS portions weighing 70 ± 5 g (approximately 4 × 6 cm² and 1 cm thick) were aseptically excised for experimental use. The SMTS of beef or camel were then randomly assigned to one of six groups: control camel and beef steaks wrapped in aluminum foil only (CC and BC), camel and beef steaks wrapped in aluminum foil and covered with either *Phoenix dactylifera* fronds (CPDF, BPDF, W/W) or *Leptadenia pyrotechnica* (CLP, BLP, W/W) at a weight of 10% (W/W). The allocation was precisely designed to ensure that the two carcasses of SMTS steaks were incorporated into each of the six treatments. A total of twelve steaks—two replicates of six pieces each—were utilized in the individual treatment. Enveloped in labelled aluminium foil and carelessly positioned on the stainless-steel grill, they were roasted for 40 minutes at 150 °C, with rotations occurring every 20 minutes. Ten grammes of the diced sample from each grilled steak were utilized for the PAH analysis.

pH analysis

Using pH-meter electrodes (Jenway 3510 pH-meter, Cole-Parmer, Staffordshire, UK), the raw meat pHU were assessed directly on the day of the experiment.

Estimation of purge loss, Water holding capacity and cooking losses

The water-holding capacity (WHC), purge losses (48 hours), and cooking losses of the SMTS were evaluated in accordance with our earlier study (Nowar et al., 2025; Younis et al., 2025).

Polycyclic aromatic hydrocarbon (PAH) extraction

A portion of 10 grams of each frozen sample was used to extract and purify PAHs in grilled samples for estimation using gas chromatography–mass spectrometry (GC-MS) (Thermo Scientific TRACE GC UltraTM system, Thermo Fisher Scientific, Waltham, MA, USA) (Rascón et al., 2019), which is thoroughly described in our recently published article. and fully outlined in our recently published article (Nowar et al., 2025). Mass spectrometric settings, GC operating conditions, and standard curve estimates were established in compliance with Rascón et al (2019).

Statistical analysis

SPSS Version 22 (SPSS Inc., Chicago, IL, USA) was used to analyze the data. A two-way ANOVA test was used to examine the effects of meat species (beef and camel) and plant-wrapping type on the amounts of polycyclic aromatic hydrocarbons in grilled SMTS. The means and overall standard errors of the results are shown. Any P-value less than 0.05 was regarded as a significant difference.

3. RESULTS

There is a statistically significant difference in pH between camel and beef meat groups, with camel exhibiting greater pH than beef ($P < 0.05$). The ANOVA test demonstrated no significant differences in water holding capacity or purge loss between raw camel and beef meat (p-values of 0.856 and 0.275, respectively). Although beef meat provided a visibly larger output (4.66) than group c (3.37), the p-value was, indicating no statistically significant difference.

Table 1. physicochemical traits of control camel and beef *Musculus semimembranosus and* semitendinosus steaks

Group	Minimum	Maximum	Mean	SE	MSE	P value
pH						
Camel control	6.52	6.59	6.565	0.016	0.033	<0.001
Beef control	6.38	6.42	6.398	0.009		
WHC						
Camel control	52.75	74.46	67.92	2.86	2.435	0.856
Beef control	56.47	79.57	68.87	4.39		
Purge loss						
Camel control	1.78	5.23	3.37	0.502	0.568	0.275
Beef control	1.78	7.99	4.66	1.069		

[1] water holding capacity (WHC) .
[2] Different small letters within the row and/or column show significant differences between treatments and and/or marination time ($p < 0.05$).

No statistically significant change in cooking loss was noticed when camel and beef were grilled in a hot air oven under control conditions or whilst wrapped in *LP* or *PDF* ($P > 0.05$). However, only camel meat wrapped with Phoenix dactylifera frond showed the lowest cooking loss

($P < 0.05$). Additionally, although there was no statistically significant difference, both meat species wrapped in *PDF* or *LP* produced less cooking loss than control ($P > 0.05$). Overall, there was no discernible variation in cooking loss across species, treatments, and their interactions.

Statistical analysis revealed a significant impact of species, treatment, and interaction on WBSF ($P < 0.05$). In particular, control camel meat was associated with higher *WBSF* than beef. Compared to the control, wrapping camel meat and beef with *LP* or *PDF* dramatically reduced *WBSF* ($P < 0.05$).

Benzo[a]pyrene (B[a]P) and PAH4 were significantly impacted by species, treatment, and interaction, according to statistical analysis ($P < 0.05$). Compared to BSMTS, camel SMTS had greater levels of PAH4 and benzo[a]pyrene (B[a]P) ($P < 0.05$). In both treatments and control, the present intense hot air oven grilling produced levels of benzo[a]pyrene (B[a]P) and PAH4 that were greater than the maximum permissible levels. Lowest levels of Benzo[a]pyrene (B[a]P) and PAH4 were connected to BSMTS and CSMTS wrapped with LP, followed by those wrapped with PDF ($P < 0.05$).

Table 2. Cooking Loss, tenderness traits and PAHs levels of grilled camel and beef *Musculus semimembranosus and* semitendinosus steaks

Traits	Group	Control	LP	PDF	MSE	P value
Cooking Loss	BSMTS	49.92^{ab}	46.60^{bc}	46.43^{bc}	0.795	0.566
	CSMTS	50.14^{a}	48.14^{ab}	46.13^{c}		
WBSF	BSMTS	6.31^{b}	4.37^{d}	5.55^{bc}	0.330	<0.001
	CSMTS	9.6^{a}	4.86^{cd}	4.2^{d}		
PAHs						
B[a]P[1]	BSMTS	139.28^{c}	12.28^{f}	67.57^{e}	20.810	<0.001
	CSMTS	259.39^{a}	91.18^{d}	154.82^{b}		
PAH4[1]	BSMTS	146.24^{c}	18.53^{f}	73.97^{e}	31.030	<0.001
	CSMTS	314.04^{a}	107.88^{d}	161.82^{b}		
GLM[1]						

P value	Cooking Loss	WBSF[1]	B[a]P	PAH4
Sp[1]	0.745	<0.001	<0.001	<0.001
T[1]	0.194	<0.001	<0.001	<0.001
Sp×T[1]	0.892	<0.001	<0.001	<0.001

[1]Control (Cont); *Leptadenia pyrotechnica* (LP), Phoenix dactylifera frond (PDF), Species (Sp), Treatment (T), Storage(St), Warner Bratzler shear force (WBSF), General linear Model (GLM). Polycyclic aromatic hydrocarbons (PAH4), including sum of Benz [a] anthracene (BaA), chrysene (Chr), benzo [b] fluoranthene (BbF), and Benzo[a]pyrene (B[a]P)
[2] Different small letters within the row and/or column show significant differences between treatments and and/or marination time ($p < 0.05$).

4. DISCUSSION

The purpose of this study was to evaluate workable, field-appropriate strategies for utilizing plant-based wrapping materials to lessen the production of hazardous PAHs in grilled meat. The impact of meat type (beef vs. camel) on PAH levels during grilling was also investigated. Natural plant-based wrapping techniques have not been extensively investigated as a means of reducing the production of PAHs while grilling (Farhadian et al., 2011). Physicochemical characteristics' contribution to PAH production during grilling is also poorly understood (Nowar et al., 2025).

Overall, the physicochemical quality of the beef and camel steaks under study, including WHC and purge loss calculated before grilling, did not differ noticeably. Additionally, grilled beef and camel steaks showed no appreciable difference in cooking loss across species, treatments, and their interactions. There was only one difference in pH, with camel showing a higher pH than beef ($P < 0.05$). Furthermore, there was reduced cooking loss from both meat species wrapped in *PDF* or *LP* than the control group ($P > 0.05$). Prior research showed that camel meat was harder and had a higher drip loss rate than beef samples (Manheem et al., 2023). These findings are contradicted by our earlier comparison of Egyptian camel and beef meat, but the higher pH of the camel meat under investigation is consistent with the widely held belief that camel meat has a greater pH and cooking loss than beef (Younis et al., 2025). Glycogen storage and other intrinsic factors significantly affect the pH and glycolysis of camel meat. More specifically, meat from camels has been found to have a higher final pH (~5.8–6.2) and a longer pH drop than beef (~5.4–5.7). This is because camel meat has lower glycolytic enzyme activity and glycogen stores (Alamin et al., 2015; Hassanien et al., 2022; Manheem et al., 2023).

According to several research studies, camels' higher collagen content and lower amounts of intramuscular fat result in higher Warner-Bratzler shear force (WBSF) values (Reza Gheisari et al. 2009; Kadim and Mahgoub 2008; Mohamed et al. 2024; and Eskandari et al. 2013). This explains the coarser texture and faster and greater shrinkage loss of camel meat after cooking (Hassanien et al., 2022; Manheem et al., 2023).

Meat quality and, most importantly, safety are impacted by processing techniques (Ciecierska et al., 2025). The findings of previous research demonstrated that tactics for reducing PAHs can be used either before (or during) grilling or smoking (barrier approaches) or after (removal methods). The primary tactics that can be used before grilling or smoking are marinating, preheating the items, using fuel that is low in lignin, using a filter, and collecting juice and fat to prevent them from dripping into the flames. Following the grilling or smoking process, the items are either stored in low-density or high-density polyethylene, or their surfaces are cleaned with hot water (60 °C) (Iko Afé et al., 2020). Our previous research indicated that higher PAH levels were associated with camel meat, which may be related to the meat's increased pyrolysis during cooking due to increased moisture loss (Nowar et al., 2025). However, here, both control meat kinds exhibited comparable cooking loss. Comparing wrapped and unwrapped samples, research has shown that the total PAHs are reduced by 40–81% on average (Farhadian et al., 2011).

The current long grilling period (40 min) was linked to violative levels of PAH4 and benzo[a]pyrene, which is different from our charcoal grilling findings (20 min) (Nowar et al., 2025). However, even here, camel meat is still associated with greater amounts of benzo[a]pyrene and PAH4, and wrapping significantly lowered production levels. The effectiveness of wrapping materials in mitigating PAHs may be related to their antioxidant content and their ability to avoid direct flame contact, which lowers pyrolysis. The type of plant, the thickness of the wrapping, the temperature of the grill, and the distance from the heat source would all affect the mitigation in both cases (Rose et al., 2015).

The PAH reduction during grilling was also observed when samples of beef and poultry were wrapped in banana tree leaves or aluminum foil (Farhadian et al., 2011). The study has shown that in beef samples, wrapping in aluminum foil results in a 39% reduction in fluoranthene (Fln) and a 100% reduction in benzo(a)pyrene (BaP) and

benzo(b)fluoranthene (BbFln). Beef samples wrapped in banana tree leaves have an 81% lower BaP content, an 85% lower BbFln concentration, and a 32% lower Fln content. BaP and BbFln are completely reduced when chicken samples are wrapped in aluminum foil. However, using banana tree leaves results in a higher reduction in ∑PAH3 content (80%) than using aluminum foil (73%) (Farhadian et al., 2011). An earlier Polish study revealed that properly selecting grilling equipment, such as utilizing electric grilling instead of charcoal, using aluminum trays when cooking with charcoal, and marinating the meat before grilling, is an important mitigating approach (Ciecierska et al., 2025). Meanwhile, grilling pig neck loins on a charcoal barbecue without an aluminum tray resulted in the highest PAH levels, exceeding Commission Regulation (EU) No. 915/2023 (Ciecierska et al., 2025). The ceramic contact grill exhibited the lowest overall contamination levels (Ciecierska et al., 2025).

Another possible method to reduce the generation or accumulation of PAHs in food items is to reduce these free radicals by adding antioxidants or radical scavengers, especially during the pre-treatment phase (Min et al., 2018; Singh et al., 2023). The phenolic profile of *L. pyrotechnica*, which includes ferulic acid, vanillin, and caffeic acid, has been linked in several studies to the plant's health advantages (Khalid, 2012; Khasawneh, 2011). While currently there is no quantitative investigation of date palm leaves (*DPL*) molecules, many qualitative analyses concur that the primary antioxidants of *PDF* are glycosylated flavonoids (Manai et al., 2024). This fibrous biomass has also been found to contain phenolic acids, including protocatechuic, p-coumaric, and ferulic acids (Chakroun et al., 2016). However, the *PDF* phenolic complexes made up of carbohydrates and lignocellulosic molecules might impede the biological characteristics of phenolics (Manai et al., 2024). However, these lignocellulosic materials have thermal endurance (Alhamzani and Habib, 2021), emphasizing the potential advantages of releasing bioactive compounds into wrapped meat during grilling and providing functional meals with biological value that may reduce PAH generation.

The moisture, along with antioxidants provided by universal and pork marinades, the Polish study found PAH contamination reduced by 24-29% for four heavy PAHs and 31-32% for fifteen PAHs, but the honey mustard marinade increased their accumulation in grilled products by 13% for four PAHs and 12% for fifteen PAHs (Ciecierska et al., 2025). Similar to the mitigating effect of wrapping, filling pork with dried fruits reduced the PAH level during thermal treatment. When compared to roasted pork loin, which had a total PAH concentration of 7.4 ng/g, roasting the meat with apricots, prunes, and cranberries reduced the content by 35%, 48%, and 58%, respectively. Additionally, the cranberries had the strongest inhibitory effect on benzo(a)pyrene production (Bulanda and Janoszka, 2023).

5. CONCLUSIONS

Camel meat has a higher pH and is naturally tougher than beef. *Leptadenia pyrotechnica* and *Phoenix dactylifera* frond wrapping enhanced tenderness and reduce cooking loss, particularly in camel meat. Despite the fact that species did not differ substantially in their ability to retain water or expel it, the use of natural wrapping offers potential functional benefits in terms of meat quality, especially in terms of tenderness. Camel SMTS had higher levels of PAH4 and benzo[a]pyrene (B[a]P) than BSMTS. Plant-wrapping decreased PAHs in comparison to the control.

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