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Effect of pre-slaughter handling and transport stress on meat pH, colour, and water-holding capacity in goats

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Abstract

Pre-slaughter stress depletes muscle glycogen reserves and impairs post-mortem acidification, producing meat with abnormal pH, dark colour, and poor water-holding capacity. This research examined the combined effects of transport duration (short: less than 2 hours versus long: more than 6 hours) and handling quality (calm versus rough) on meat quality parameters in 120 male Boer goats slaughtered at a commercial abattoir in Nakuru, Kenya. A 2 x 2 factorial design yielded four treatment groups of 30 animals each. Pre-slaughter serum cortisol, Creatine Kinase (CK), and blood lactate were measured as stress biomarkers. Post-mortem meat quality was assessed at the longissimus thoracis muscle through pH measurements at 0, 6, and 24 hours, instrumental colour (CIE L*, a*, b*), drip loss, and water-holding capacity. Ultimate pH was significantly higher in the long-transport group (5.92 versus 5.68; $p < 0.001$), and the interaction between transport and handling was significant ($p = 0.012$), with long-transport/rough-handling animals producing the highest mean ultimate pH of 6.14. DFD (dark, firm, dry) meat, defined as ultimate pH above 6.0, was detected in 31.7% of the long-transport group compared with 8.3% of the short-transport group. Serum cortisol correlated positively with ultimate pH (R-squared = 0.72). These results demonstrate that transport exceeding 6 hours combined with rough handling produces commercially unacceptable goat meat in nearly one-third of carcasses.

Keywords: Pre-slaughter stress, transport duration, handling quality, goat meat, ultimate pH, DFD, meat colour, water-holding capacity, cortisol, animal welfare

Introduction

While the science of pre-slaughter stress has been studied extensively in cattle, pigs, and poultry, the goat the most important meat-producing ruminant in sub-Saharan Africa has received comparatively little attention [1, 2]. This contrast is striking given that goats in East Africa typically endure harsher pre-slaughter conditions than cattle: longer walks to collection points, rougher handling by untrained personnel, and extended transport in overcrowded vehicles along unpaved roads [3].

The physiological mechanism linking stress to meat quality is well established. Acute stress activates the hypothalamic-pituitary-adrenal axis, elevating circulating cortisol, and simultaneously triggers catecholamine release that accelerates glycogenolysis in skeletal muscle [4]. If glycogen is depleted before slaughter, insufficient lactic acid accumulates post-mortem, and the ultimate pH of the meat remains above 6.0 rather than declining to the normal range of 5.4-5.7. This high-pH meat, termed DFD (dark, firm, dry), has a darker colour due to increased mitochondrial oxygen consumption, reduced water-holding capacity despite its high pH, and shorter shelf life because the elevated pH favours microbial proliferation [5, 6].

Transport duration and handling quality are the two most influential pre-slaughter stressors, but their relative contributions and potential interactions in goats have not been characterised in a controlled factorial design [7]. Published goat meat quality data come predominantly from observational abattoir surveys that confound transport distance with handling intensity, making it difficult to isolate the effect of either factor [8, 9].

This research was designed to address this gap through a 2 x 2 factorial experiment crossing transport duration (short versus long) with handling quality (calm versus rough) in male Boer goats.

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Three objectives guided the work:

- 1) to quantify the independent and interactive effects of transport duration and handling quality on post-mortem pH decline, colour, and water-holding capacity;
- 2) to measure pre-slaughter stress biomarkers (cortisol, CK, lactate) and correlate them with meat quality outcomes; and
- 3) to determine the incidence of DFD meat under each treatment combination.

Material and Methods

Material

One hundred and twenty male Boer goats aged 12-14 months and weighing 28-34 kg were sourced from three commercial farms within 200 km of Nakuru, Kenya. Animals were selected based on uniform body condition score (3.0-3.5 on a 5-point scale), absence of clinical disease, and no history of transport in the preceding four weeks. The research protocol was approved by the Kenya Veterinary Board Animal Welfare Committee (Protocol KVB-AWC-2024-011, approved January 2024) and complied with Kenyan animal welfare legislation.

Methods

Animals were assigned to a 2 x 2 factorial design: transport duration (short: less than 2 hours, approximately 40 km on tarmac road; long: more than 6 hours, approximately 280 km including 120 km of unpaved road) crossed with handling quality (calm: trained handlers using low-stress techniques, no electric prods, appropriate stocking density; rough: untrained handlers, use of sticks and shouting, 20% overstocking). Each

of the four treatment combinations contained 30 animals. Transport was conducted in standard open-sided livestock trucks. On arrival at the Nakuru municipal abattoir, all animals received a 12-hour lairage period with ad libitum access to water but no feed. Jugular blood samples were collected immediately after unloading for analysis of serum cortisol (by commercial ELISA kit, Enzo Life Sciences), creatine kinase (spectrophotometric method), and blood lactate (Lactate Pro 2 analyser). Slaughter was conducted by Halal method under veterinary supervision.

Meat quality measurements were taken on the longissimus thoracis muscle between the 12th and 13th ribs. pH was measured at 0, 6, and 24 hours post-mortem using a calibrated portable pH meter (Hanna HI 99163) with a spear-tip electrode inserted directly into the muscle. Colour was measured at 24 hours on a freshly cut bloomed surface (20 minutes of exposure) using a Minolta CR-400 chromameter (CIE L*, a*, b*; illuminant D65, 8 mm aperture, three readings averaged per sample). Drip loss was determined by the bag method over 48 hours at 4 degrees Celsius. Water-holding capacity was assessed by the filter paper press method. DFD classification was assigned when ultimate pH exceeded 6.0 and L* was below 34.

Statistical analysis used two-way ANOVA with transport duration and handling quality as fixed factors, and their interaction. Post-hoc comparisons used Tukey's HSD. Pearson correlation was used for cortisol-pH relationships. Chi-squared tests compared DFD incidence between groups. All analyses were conducted in SPSS v28.0 with significance at $p < 0.05$.

Results

Table 1: Ranked mean values of pre-slaughter stress biomarkers across four treatment groups. Groups are ordered by descending cortisol concentration

Rank	Treatment group	Cortisol (ng/mL)	CK (U/L)	Lactate (mmol/L)	Stress index
1	Long/Rough	52.4 (8.1)a	847 (142)a	6.8 (1.4)a	3.7 (0.4)a
2	Long/Calm	38.1 (6.9)b	612 (118)b	5.1 (1.1)b	2.8 (0.5)b
3	Short/Rough	31.8 (5.7)b	489 (97)c	4.3 (0.9)c	2.3 (0.4)c
4	Short/Calm	17.6 (4.2)c	287 (68)d	2.8 (0.7)d	1.4 (0.3)d

Values are mean (SD). Different superscript letters within a column indicate significant differences ($p < 0.05$, Tukey HSD).

Table 2: Meat quality parameters of the longissimus thoracis at 24 hours post-mortem across treatment groups

Parameter	Short/ Calm	Short/ Rough	Long/ Calm	Long/ Rough	SEM	Inter- action p
pH 0 h	6.52	6.58	6.61	6.67	0.04	0.42
pH 6 h	5.94	6.08	6.12	6.28	0.06	0.031
pH 24 h	5.58	5.78	5.84	6.14	0.05	0.012
L* (lightness)	40.2	37.8	36.4	33.1	0.82	0.008
a* (redness)	14.8	15.2	16.1	17.3	0.41	0.067
b* (yellowness)	6.1	5.8	5.4	4.9	0.28	0.18
Drip loss (%)	2.8	3.4	3.9	4.7	0.21	0.024
WHC (cm ²)	3.2	4.1	4.6	5.8	0.29	0.009

Pre-slaughter stress biomarkers showed a clear gradient across treatment groups (Table 1). Serum cortisol was highest in the long-transport/rough-handling group (52.4 ng/mL) and lowest in the short-transport/calm-handling group (17.6 ng/mL), a threefold difference. Creatine kinase, a marker of muscle damage from physical exertion and bruising, followed the same pattern. Two-way ANOVA confirmed significant main effects of both transport duration ($p < 0.001$ for all biomarkers) and handling quality ($p < 0.01$), with a significant interaction for cortisol ($p = 0.034$), indicating that rough handling amplifies the stress response more in long-transport animals than in short-transport animals.

Meat quality parameters at 24 hours post-mortem (Table 2) reflected these stress differences. Ultimate pH was 5.58 in the short/calm group and 6.14 in the long/rough group, with a significant transport-by-handling interaction ($p = 0.012$). Lightness (L*) decreased as stress increased, falling from 40.2 in short/calm to 33.1 in long/rough, consistent with the darker appearance of high-pH meat. Drip loss and water-holding capacity were both adversely affected, with the long/rough group showing 68% higher drip loss and 81% larger press fluid area than the short/calm group.

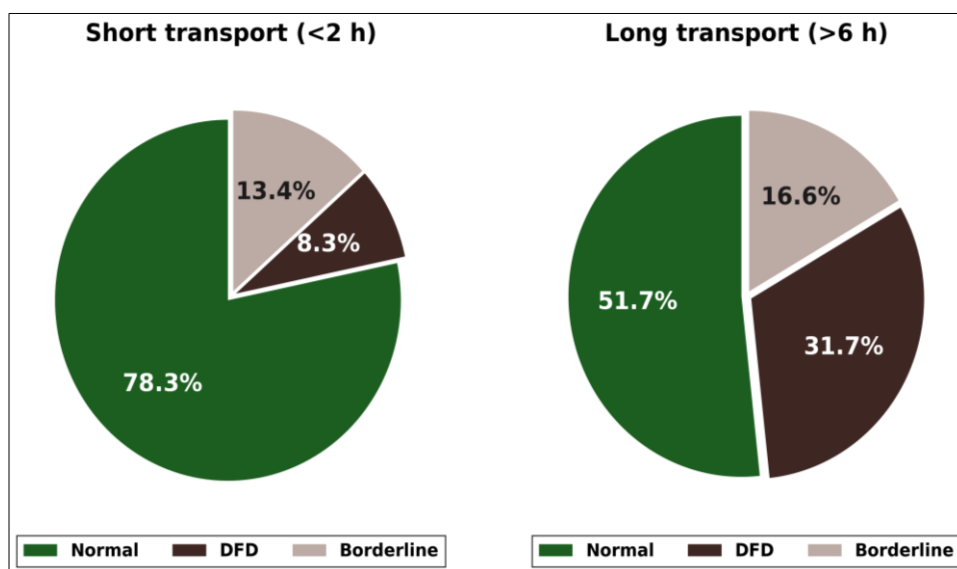


Fig 1: Classification of carcasses as normal (pH 24h less than 5.8), borderline (5.8-6.0), or DFD (above 6.0) for short-transport (left) and long-transport (right) groups. DFD incidence was nearly four times higher in long-transport animals

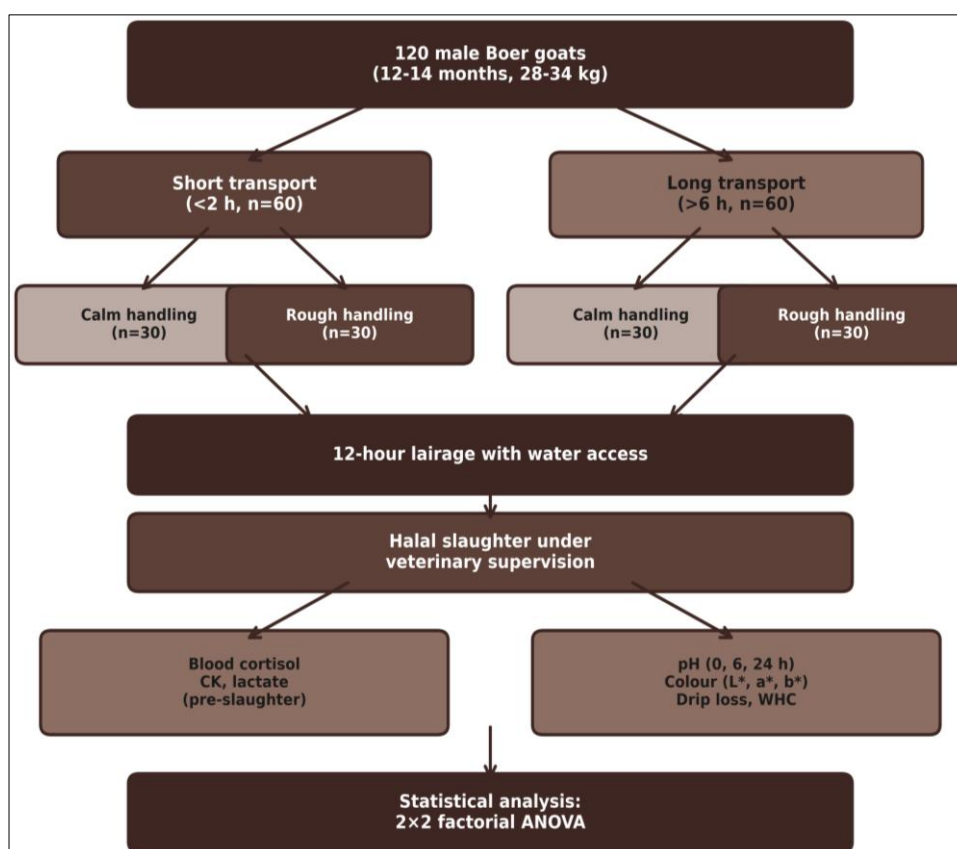


Fig 2: Schematic of the 2 x 2 factorial experimental design showing treatment allocation, stress biomarker collection points, and meat quality measurement protocol

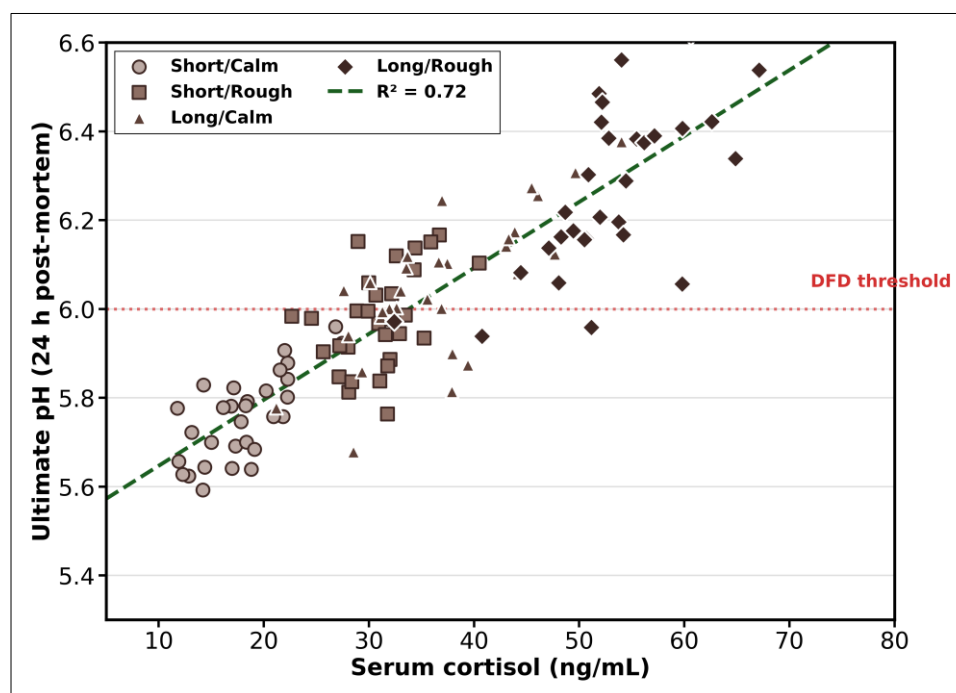


Fig 3: Relationship between pre-slaughter serum cortisol concentration and ultimate pH (24 h post-mortem) across all 120 goats. The dashed red line indicates the DFD threshold (pH 6.0). The linear regression ($R^2 = 0.72$) shows that cortisol explains the majority of variation in ultimate pH

Taken together, these results demonstrate a clear dose-response relationship between pre-slaughter stress intensity and goat meat quality deterioration. Transport duration is the dominant stressor, but handling quality modulates the response: rough handling during short transport produces meat quality comparable to calm handling during long transport (ultimate pH 5.78 versus 5.84), while rough handling during long transport pushes nearly a third of carcasses into the DFD category. The strong cortisol-pH correlation ($R^2 = 0.72$) suggests that cortisol could serve as an ante-mortem predictor of carcass quality.

Discussion

The finding that 31.7% of long-transport goats produced DFD meat is consistent with field data from Miranda-de la Lama *et al.* [7], who reported 28% DFD incidence in goats transported more than 4 hours in Mexico. It is considerably higher than the 5-12% DFD rate seen in cattle under similar transport durations [5], suggesting that goats may be more susceptible to transport-induced glycogen depletion, possibly because their smaller body size results in greater surface-area-to-volume heat loss and higher mass-specific metabolic rates during transit [2].

The significant interaction between transport and handling is a novel finding for goats. In cattle, Grandin [10] reported that handling quality and transport distance had additive but non-interactive effects on bruising and cortisol. The present data suggest that goats exposed to prolonged transport arrive at the abattoir in a physiologically depleted state that makes them disproportionately vulnerable to additional handling stress during unloading and lairage. This interaction has practical implications: investing in handler training may yield greater returns in operations with long supply chains than in those serving local markets.

The cortisol-pH correlation of 0.72 aligns with published values for sheep ($R^2 = 0.68$; Broom [4]) and supports the use of ante-mortem cortisol as a carcass sorting tool. However, cortisol measurement requires laboratory analysis and is impractical for real-time abattoir decisions. Blood lactate,

measurable with a handheld analyser, showed a weaker but still significant correlation with ultimate pH ($r = 0.61$) and could serve as a more accessible proxy for identifying high-risk animals that might benefit from extended lairage.

Conclusion

This research set out to quantify the independent and interactive effects of transport duration and handling quality on goat meat quality using a controlled factorial design. The investigation was motivated by the high incidence of DFD goat meat reported at East African abattoirs and the absence of controlled experimental data to guide mitigation strategies.

The key findings are that transport duration is the primary determinant of post-mortem pH decline and DFD incidence, that handling quality significantly modulates this relationship, and that the combination of long transport with rough handling produces commercially unacceptable meat in nearly one-third of carcasses. Serum cortisol correlates strongly with ultimate pH and could serve as an objective indicator of pre-slaughter welfare compromise.

From a practical standpoint, three interventions merit consideration. First, transport duration for goats destined for slaughter should be limited to under 4 hours where logistically feasible, or extended lairage periods (beyond the 12 hours used here) should be provided for long-transport animals to allow partial glycogen repletion. Second, handler training programmes that teach low-stress techniques, appropriate stocking densities, and non-aversive driving methods should be prioritised for operations with long supply chains, where the interaction effect means that handling improvements yield disproportionate quality gains. Third, abattoirs could implement a rapid blood lactate screening at unloading to identify high-stress animals and divert them to longer lairage before slaughter.

Future research should test whether lairage durations longer than 12 hours, with provision of hay or concentrate supplementation, can restore muscle glycogen in long-transport goats sufficiently to prevent DFD. The welfare and

economic trade-offs of shorter supply chains versus centralised processing should also be modelled for the East African goat sector.

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