105 (2026) 107379

Contents lists available at ScienceDirect

Poultry Science

journal homepage: www.elsevier.com/locate/psj

Full-Length Article

Black soldier fly larvae meal effects on broiler performance, carcass, and meat traits: A meta-analysis of rearing substrates

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ARTICLE INFO

Keywords:
Hermetia illucens
Meat quality
Meta-analysis
Organic substrate
Sustainable protein

ABSTRACT

Black soldier fly larvae meal (BSFLM) is a sustainable alternative to conventional protein sources in poultry nutrition. However, the influence of rearing substrate type on broiler performance, carcass traits, and meat quality, and the factors that moderate this relationship, remains poorly understood. This meta-analysis quantified the effects of dietary BSFLM on broiler performance, carcass traits, and meat quality. A systematic search of four databases identified 15 studies published between 2015 and 2025. Random-effects models were used to calculate Hedges' *g* standardized mean differences (SMD). Pooled analysis showed that BSFLM did not significantly influence average daily feed intake (ADFI), average daily weight gain (ADG), or feed conversion ratio (FCR). However, meta-regression identified a negative relationship between higher inclusion levels and ADFI (slope = -0.0337; P = 0.0290), while growth-promoting effects were more evident during shorter-term feeding periods. Subgroup analysis further revealed that larvae reared on non-halal substrates had a significantly higher ADG (SMD = 2.22; P = 0.0055), whereas halal-reared larvae showed a slight reduction (SMD = -0.24). Carcass traits were unaffected, though strain-specific improvements in thigh and wing weights were observed in Cobb 500 broilers, which also exhibited pronounced increases in meat redness. BSFLM significantly increased muscle fat (SMD = 0.99; P = 0.0001), redness (SMD = 0.64; P = 0.0029), and ultimate pH (SMD = 0.52; P = 0.0035). Processing methods influenced water-holding capacity: oven-drying significantly reduced drip loss (SMD = -1.24), whereas sun-drying reduced thaw loss (SMD = -3.01). Both oven-drying and sun-drying also preserved nutrient integrity and improved FCR in broilers. However, yellowness tends to decline at higher inclusion levels (P = 0.0068). BSFLM supports broiler growth, carcass traits, and meat quality, with its efficacy moderated by rearing substrate, processing method, strain, inclusion level, and feeding duration. These findings provide guidance for optimizing BSFLM use at a recommended 28% inclusion level within a 37-day phase-feeding duration, with careful consideration of substrate choice, bird genetics, and processing techniques to meet both nutritional and market requirements.

Introduction

The global poultry industry faces the challenge of meeting escalating protein demand while mitigating the environmental and economic costs of conventional ingredients like soybean meal and fish meal (Boerema et al., 2016; Saidani et al., 2025). These sources are linked to significant concerns, including greenhouse gas emissions, water pollution, and deforestation (FAO, 2007; Khalifah et al., 2023; Sajid et al., 2023). Additionally, volatile commodity prices and competition between human and animal nutrition have escalated production costs (Gasco et al., 2019; Naimati et al., 2022; Thirumalaisamy, 2016). This has accelerated the search for sustainable alternatives to alleviate the pressure on global food resources (Mohamad et al., 2025; Mustapa and Kallas, 2023). Among these, black soldier fly larvae meal (BSFLM)

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https://doi.org/10.1016/j.psj.2026.107379
Received 16 April 2026; Accepted 1 July 2026
Available online 2 July 2026

(*Hermetia illucens*), approved by the European Commission in 2021 (European Commission Regulation, 2021), has emerged due to its superior amino acid profile, high protein (32-53%), and lipid content (25-45%) (Abd El-Hack et al., 2020; Barragan-Fonseca et al., 2019; Belperio et al., 2024; Hawkey et al., 2021).

In broiler chicken nutrition, BSFLM inclusion in isoenergetic and isonitrogenous diets has maintained (Cullere et al., 2016; Hartinger et al., 2022; Onsongo et al., 2018; Saidani et al., 2025) or improved (Dabbou et al., 2018; De Souza Vilela et al., 2021; Gariglio et al., 2019) growth performance indices at both the starter and finisher phases. Some studies, on the other hand, have reported either no significant effect (Pieterse et al., 2019) or an improvement in carcass yield and dressing percentage (Chia et al., 2021; Hoffman, 2019; Mutisya et al., 2021; Popova et al., 2020; Schiavone et al., 2019). Beyond these indices, BSFLM inclusion in broiler diets had yielded no detrimental effects on ultimate pH, color, drip loss, and cooking loss (Aslam et al., 2025; Murawska et al., 2021; Pieterse et al., 2019; Schiavone et al., 2019; Saidani et al., 2025).

While some trials found no difference in performance at replacements below 55.5% of soybean meal (Cullere et al., 2016; Onsongo et al., 2018), others noted reduced body weight and feed conversion efficiency at 15% (Dabbou et al., 2018) or 100% inclusion (Facey et al., 2023; Fruci et al., 2023). Popova et al. (2020) observed a reduction in thigh weight, an increase in breast weight, and a reduction in muscle pH. These discrepancies have often been attributed to varying inclusion levels, bird strain, processing methods, substrates used, and experimental protocols (Saidani et al., 2025; Tschirner and Simon, 2015). Despite numerous original studies on BSFLM utilization, the systematic synthesis of its effects via a meta-analytic approach remains limited. Hayat et al. (2024) and Martínez Marín et al. (2023) in their effort primarily focused on the effects on performance and metabolizable energy, while Chhetri et al. (2025) evaluated production performance and meat quality without exploring the sources of between-study variation, despite the profound influence of substrate type on larval chemical composition.

A critical yet overlooked dimension in this field is the religious and ethical status of the rearing substrate. In a global Halal market projected to reach $1.94 trillion by 2028 (Kawsar, 2025), the halal status of poultry is increasingly scrutinized not only at the slaughter level (Sazili et al., 2023), but also at the feed level (Hamdan et al., 2018). Under Islamic jurisprudence, interpretations regarding permissible substrates for insect rearing vary across different schools of thought (madhahib) and contemporary scholarly bodies, including regional fatwa authorities, particularly concerning the transformation and purity status of substrates during bioconversion processes (Khairiah et al., 2024; Dahaman and Mohd Yusof, 2024). While some scholars permit larvae to be reared on materials classified as najis (impure) provided the resulting product does not retain impurity attributed to odor, color, or taste, others advocate stricter controls, including purification or quarantine periods before the product is considered permissible for consumption (Al-Bukhari, 2002; Al-Mardawi, 2003; Indonesian Ulama Council, 2019; Jamaludin et al., 2011, 2018, 2023; Maryuliano and Andarwulan, 2024). Substrates are therefore classified by origin as “halal” (permissible plant-based or certified animal-derived materials), “non-halal” (najis materials like swine, fecal matter, or blood), and “mashbooh” (substrates of doubtful or unclear halal status, including mixed municipal waste or kitchen waste) (Mohammad, 1993; Regenstein et al., 2003). While some Islamic scholars mandate a quarantine period to ensure the expulsion of impurities (Jamaludin et al., 2011), this process imposes significant logistical and economic burdens on the poultry and general livestock industry (Rahman, 2012). This, therefore, makes the initial selection of rearing substrates a pivotal factor in commercial viability (Asiry et al., 2026; Dahaman and Mohd Yusof, 2024; Jamaludin et al., 2021). From a jurisprudence perspective, the use of substrates already free from najis avoids these logistical burdens (Jamaludin et al., 2023; Mazuki, 2025; Noorsiah and Sariwati, 2016). Yet, many studies continue to utilize non-halal substrates, particularly fecal sludge (Kirimi et al., 2025; Mutisya et al., 2021) or mixed organic or industrial waste (Facey et al., 2023; Modupe et al., 2025; Saidani et al., 2025) for black soldier fly (BSF) larvae production.

Considering this, and to the best of our knowledge, no study has systematically defined, in context, how the source of rearing substrate (halal and non-halal) impacts the production indices of broiler chickens. Therefore, this study was conducted to provide a rigorous, evidence-based synthesis of the impact of BSFLM on growth performance, carcass traits, and meat quality. Our study aims to quantify the overall effect of BSFLM and to explore sources of variation through subgroup analysis and meta-regression.

Materials and methods

Data search, screening, and study selection

A systematic literature search was conducted on December 3, 2025, across four online databases, including ScienceDirect, PubMed, Scopus, and Google Scholar. The research question was formulated using the PICO framework (Schmid et al., 2020), which identified our key elements: population (broiler chickens), intervention (black soldier fly larvae meal), comparator (basal diet without BSFLM inclusion), and outcomes (growth performance, carcass, and meat quality traits). Following the PRISMA screening guide (Page et al., 2021), articles were retrieved using a combination of keywords tailored to each database (see supplementary Table 1). This meta-analysis was prospectively registered in the Open Science Framework (https://doi.org/10.17605/OSF.IO/EVMWJ). Only peer-reviewed studies published between January 2015 and November 2025 were included in the meta-analysis. For a study inclusion, our criteria stipulated that they must have: (i) investigated the effect of BSFLM inclusion on broiler performance, carcass traits, and meat quality; (ii) been published in an open-access peer-reviewed English journal; (iii) used randomized controlled trials; (iv) reported the mean and standard deviation or standard error; (v) reported at least one parameter of interest. Conversely, studies were excluded if they: (i) used other insect species; (ii) evaluated BSFL oil or frass instead of meal; (iii) failed to report the substrate used; (iv) were not published in English; (v) fed BSFLM to species other than broilers; or (vi) did not report a parameter of interest.

Following a two-step selection and screening process described by (Nuamah et al., 2024) and summarized in a PRISMA diagram (Fig. 1), an independent screening of 901 records stored in Zotero (Version 7.0.22) was conducted by two reviewers (U.M.O. and E.N.). Disagreements between reviewers at either stage were resolved through discussion, and where consensus could not be reached, a third reviewer (M.N.H) was consulted to resolve the disagreement. After removing duplicates, the first step involved screening titles and abstracts to exclude review papers, conference papers, theses, book chapters, and abstracts, while the second step involved a full-text assessment to confirm eligibility. A total of 15 full-text articles met the eligibility criteria and were included in the meta-analysis.

Risk of bias and quality assessment

The quality of the included studies was evaluated using the Cochrane Collaboration’s SYRCLE risk of bias tool. Specific domains assessed include baseline characteristics, selective outcome reporting, random housing, random outcome assessment, completeness of outcome data, and other potential biases. Each domain was evaluated using a three-level judgment scale, including “low risk,” “high risk,” or “unclear risk”, with clear justifications provided for all ratings. The risk of bias summary was visualized through “traffic light” and summary bar plots generated using the Robvis visualization tool (McGuinness and Higgins, 2021).

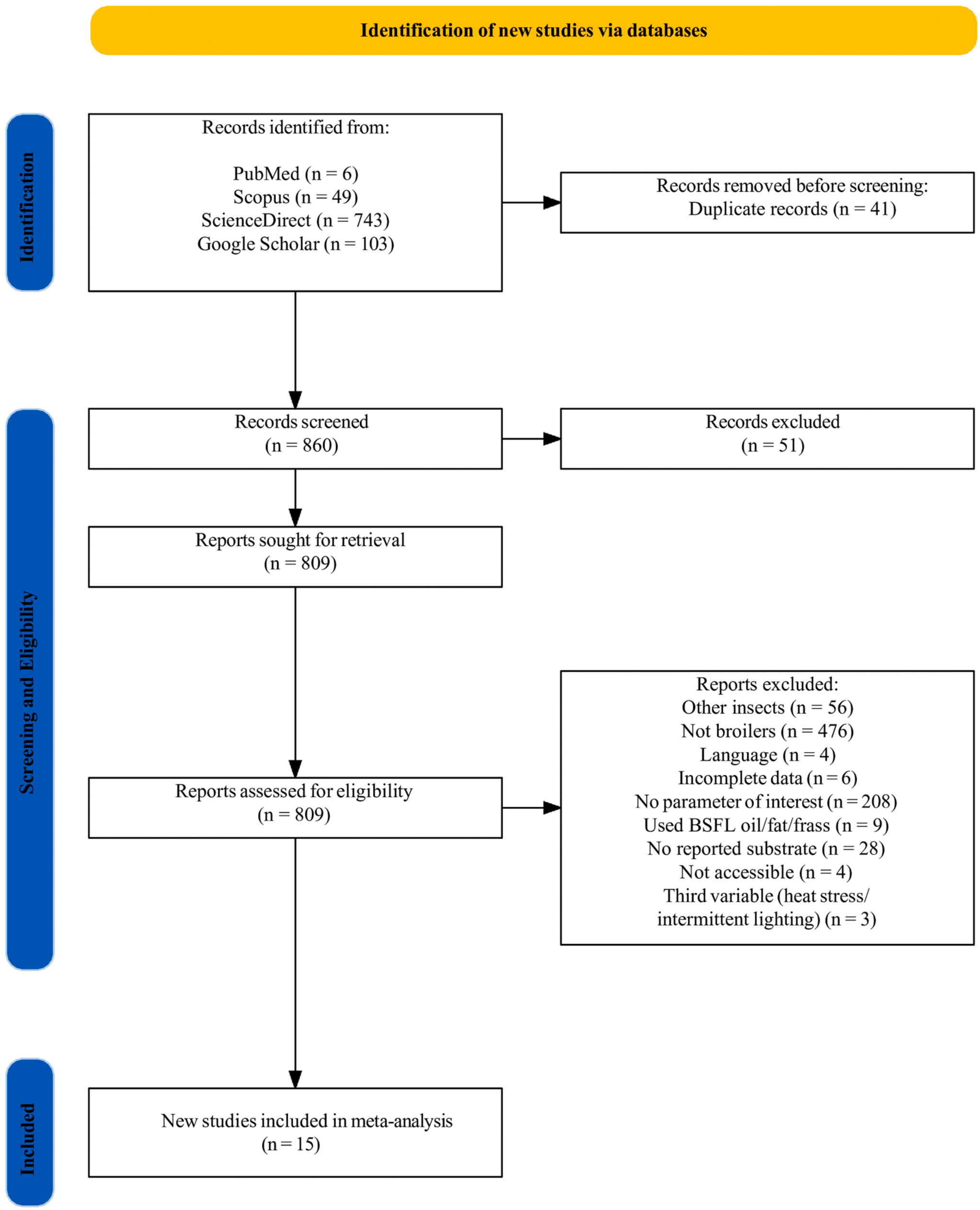

Fig. 1. Prisma diagram for the meta-analysis focused on BSFLM.

Data extraction

A two-step data extraction process was employed using a spreadsheet in Google Sheets (Google LLC, Mountain View, CA, USA). The first step involved extracting study-specific characteristics, including the author's name, publication year, country, broiler strain, feeding duration, inclusion level, housing system, substrate description, substrate type, and processing method. Data were extracted for response variables (second step), including average daily feed intake (ADFI), average daily gain (ADG), feed conversion ratio (FCR), breast, thigh, and wing weights, ultimate pH (pHu), drip loss, cook loss, thaw loss, color (lightness [L*], redness [a*], yellowness [b*]), muscle fat, and ash. Mean and standard deviation (SD) values for each response variable were recorded. Where applicable, standard errors (SEM) were converted to standard deviations using the formula $SD = SEM \times \sqrt{n}$. All carcass traits were converted to a percentage of live weight to ensure comparability. In studies reporting multiple treatment levels (BSFLM), each comparison between a treatment level and the control was treated as an independent study within the meta-analysis.

Model selection, effect measure, and statistical analysis

Selecting a random effects model to account for the fact that the study effect estimates are more variable than assumed in the fixed effect model, the effect size (standardized mean difference, SMD) was estimated using the Hedges' *g* estimator and weighted by the inverse variance method at a 95% confidence interval (CI). The SMD effect size values of 0.2-0.5, 0.5-0.8, and > 0.8 represent small, medium, and large effect sizes (Cohen, 2013).

Publication bias was visualized using funnel plots to detect asymmetry and quantified using Egger's linear regression test (Egger et al., 1997). This test was applied only to outcomes with at least 10 included studies ($K \geq 10$), as its power is significantly reduced when $K < 10$ (Sterne et al., 2011). Where significant asymmetry was detected, Vevea and Hedges' selection model (Hedges and Vevea, 1996) was applied to adjust meta-analytic effect sizes for publication bias.

The between-study variance (τ^2) was estimated using the Restricted Maximum-Likelihood (REML) estimator (Schwarzer et al., 2015). To test for the significance of τ^2, the Cochran's Q test P value of 0.10 was used. Using a percentage version of heterogeneity (I^2), it was scaled as $I^2 <$ 25% = low; 25%−50% = moderate; 50%−75% = high; 75%−100% = very high). However, to rule out the contribution of outliers to the overall effect size and heterogeneity, Baujat plots and a leave-one-out procedure (influence diagnostics) were performed. The Cook's distance and difference-in-fit plots were used to verify the influence diagnostics. Outcome variables still showing significant heterogeneity (PCochran's Q $\leq$ 0.01 and $I^2 \geq$ 50%) were addressed through subgroup and meta-regression analyses to further explore the sources of variation.

The primary subgroup analysis, defined *a priori*, was based on the rearing substrate of BSFLM, categorized as halal or non-halal. For this meta-analysis, substrate classification was based on the reported origins and compositions of the rearing substrates in the primary studies. Plant-based substrates and permissible animal-derived materials were classified as halal, whereas substrates containing swine-derived materials, fecal matter, or blood were classified as non-halal. Substrate-based subgroup analysis was performed only for outcomes (ADFI, ADG, FCR, breast, thigh, and wing) where sufficient studies reported clear substrate information. Studies lacking substrate details were included in the overall meta-analysis but excluded from substrate-based subgroup comparisons. It should be noted that potential confounding between substrate composition and halal status cannot be ruled out, as substrate origin is intrinsically linked to its categorization. This classification was adopted as an operational framework to ensure consistency and comparability across studies.

Further subgroup analysis was conducted using alternative covariates, including BSFLM processing method, housing system, and broiler strain. Additionally, subgroups were only analyzed when at least two studies contributed data to each category (n $\geq$ 2), ensuring that comparisons were based on more than a single study estimate and thus providing the minimal data required for meaningful between-subgroup differences and variance estimation (Higgins and Green, 2011). All analyses were conducted in R Statistical Software 4.5.1(R Core Team) using the 'meta' and 'metafor' packages.

Results

General characteristics of included studies

This meta-analysis was conducted to test the hypothesis that black soldier fly larval meal would positively influence broiler performance, carcass traits, and meat quality. The 15 included studies were grouped into 35 individual comparisons, as several studies evaluated multiple BSFLM inclusion levels relative to a control. The key features of these studies are summarized in Table 1. The studies were conducted across four continents (Africa, Asia, Europe and North America) in nine countries (Kenya, Italy, India, Canada, South Africa, Ghana, Malaysia, Nigeria, and Tunisia) - Fig. 2. Regarding broiler strain, Cobb 500 was predominantly used (53.33%), Ross 308 and Ross x Ross 708 each accounted for 13.33%, while Vencobb 400 and Arbor Acres were utilized in 6.67% of the studies. One study did not specify the strain used. Most strains were raised in deep litter systems (80%), followed by battery cages (13.33%) and metabolic cages (6.67%). Notably, halal substrates predominated among the included studies (60%), followed by mashbooh (doubtful or unclear halal status) (26.67%) and non-halal (13.33%). Dietary inclusion levels of BSFLM ranged from 5% to 100%, and feeding durations ranged from 21 to 49 days. The BSFLM processing

Table 1
Summary of studies used to evaluate the effects of BSFLM on broiler chicken performance, carcass traits, and meat quality.

Study	Country	Broiler strain	Feeding duration	Inclusion level	Housing system	Substrate description	[1]Substrate type	Processing method	Response variables
Adam et al. (2025)	Ghana	Cobb 500	42	10, 20, 28.6	Deep-litter	Fruit/vegetable waste	Halal	Oven-dried	ADFI, ADG, FCR
Dabbou et al. (2018)	Italy	Ross 308	35	5, 10, 15	Deep-litter	Vegetable by-product	Halal	Partially defatted	ADFI, ADG, FCR
Elangovan et al. (2021)	India	Cobb 500	21	5	Battery cage	Fruit/vegetable waste	Halal	Oven-dried	ADFI, ADG, FCR
Facey et al. (2023)	Canada	Ross x Ross 708	49	12.5, 25, 50, 100	Deep-litter	Recycled food	Mashbooh	Partially defatted	ADFI, ADG, FCR
Fruci et al. (2023)	Canada	Ross x Ross 708	35	12.5, 25, 50, 100	Metabolic cage	Plant-based food waste	Halal	Partially defatted	ADFI, ADG, FCR
Kirimi et al. (2025)	Kenya	Cobb 500	28	25, 50, 75, 100	Deep-litter	Fecal matter	Non-halal	Sun-dried	ADFI, ADG, FCR, BR, T, W
Mat et al. (2022)	Malaysia	Cobb 500	42	4, 8, 12	Deep-litter	Plant food waste	Halal	Defatted	ADFI, ADG, FCR
Modupe et al. (2025)	Nigeria	Cobb 500	42	25, 50, 75, 100	Deep-litter	Mixed food waste	Mashbooh	Sun-dried	TL
Muleya et al. (2024)	South Africa	Ross 308	21	5, 5, 10	Deep-litter	Vegetable waste	Halal	Oven-dried	ADFI, ADG, FCR, pHu, DL, BR, T, W, L, a, b
Mutisya et al. (2021)	Kenya	Cobb 500	42	75, 50, 25	Deep-litter	Pig manure	Non-halal	Oven-dried	ADFI, ADG, FCR
Onsongo et al. (2018)	Kenya	Cobb 500	42	5, 10, 15	Deep-litter	Kitchen/solid waste	Mashbooh	Oven-dried	ADFI, ADG, FCR, BR
Patel et al. (2025)	India	Vencobb 400	42	3, 6, 9	Deep-litter	Fruit/vegetable waste	Halal	Partially defatted	ADFI, ADG, FCR
Pieterse et al. (2019)	South Africa	Cobb 500	35	5, 10, 15	Battery cage	Fruit/vegetable waste	Halal	Oven-dried	pHu, TL, CL, BR, T, W, L, a, b
Saidani et al. (2025)	Tunisia	Arbor Acres	28	5	Deep-litter	Biowaste (fruit/ vegetable/food processing by-products)	Mashbooh	Full-fat	ADFI, ADG, FCR, pHu, CL, BR, T, L, a, b, fat, ash
Schiavone et al. (2019)	Italy	Unreported	35	5, 10, 15	Deep-litter	Cereal by-products	Halal	Partially defatted	pHu, DL, CL, BR, T, L, a, b, fat, ash

Abbreviations: FCR: feed conversion ratio, BR: breast, T: thigh, W: wing, CL: cook loss, DL: drip loss, TL: thaw loss, L: lightness, a: redness, b: yellowness.
[1] Mashbooh = "doubtful" or "unclear halal status".

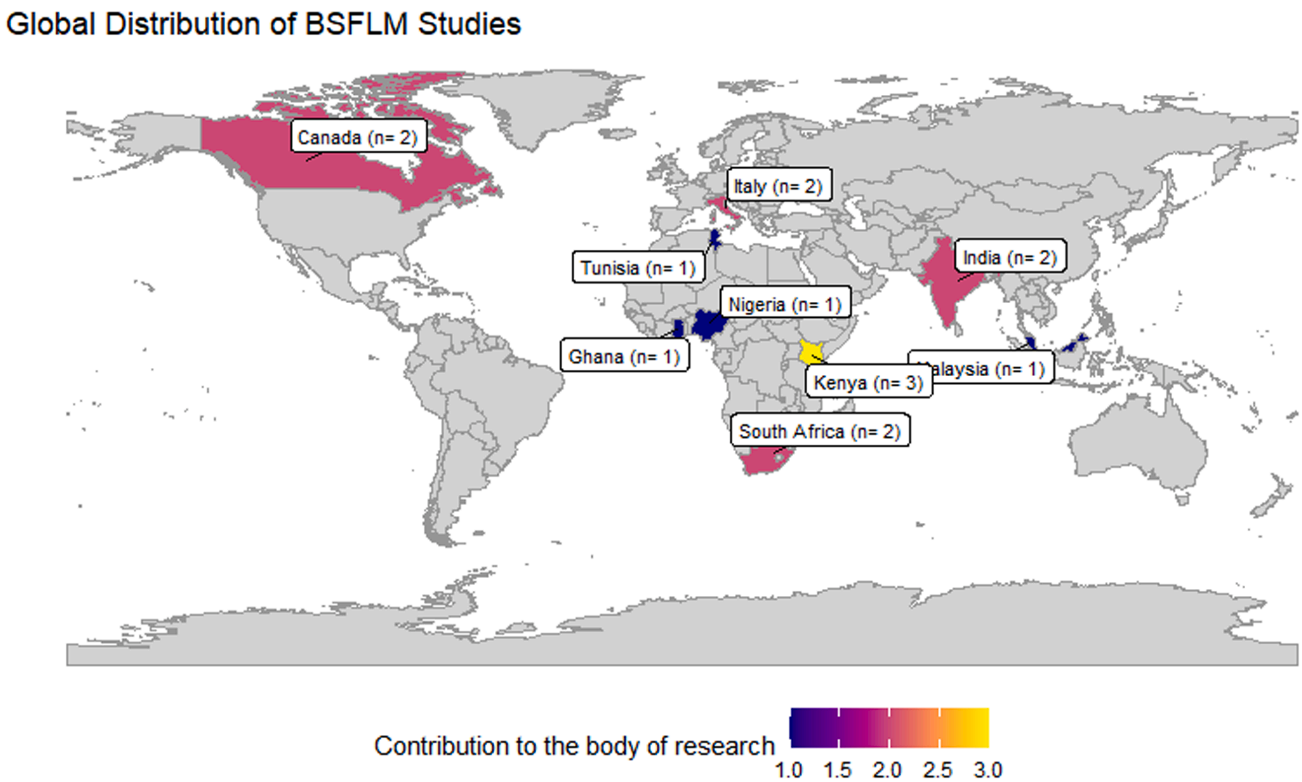

Fig. 2. Geographic distribution of studies included in the meta-analysis.

methods varied, including oven-drying (40%), partial defatting (33.33%), sun-drying (13.33%), full defatting and full-fat (6.67%).

Risk of bias assessment for included studies

Risk of bias (RoB) was assessed using the checklist of SYRCLE's RoB tool, and the results were summarized in Fig. 3. Most studies (10) were rated as having a low risk of bias across the evaluated domains, accounting for 66.67% of all judgments, and pointing to the quality of the methodology. One study (Pieterse et al., 2019) was rated unclear (6.67%), while four studies (Modupe et al., 2025; Onsongo et al., 2018; Saidani et al., 2025; Schiavone et al., 2019) were rated high risk (26.67%) for random outcome assessment. The summary of the risk of bias across all the included studies in this meta-analysis is presented in Supplementary Fig. S1.

Meta-analysis

Growth Performance. Table 2 shows that adding BSFLM to broiler diets consistently lowered ADFI (SMD = −0.93; 95% CI: −1.87 to 0.01; P = 0.0514; I^2 = 97.3%) and FCR (SMD = −0.11; 95% CI: −1.39 to 1.17; P = 0.8695; I^2 = 99.0%) compared to controls. However, its inclusion increased ADG (SMD = 0.26; 95% CI = −0.36 to 0.89; PSMD = 0.4070; I2 = 98.0%) compared with the control group.

Carcass Traits. Inclusion of BSFLM in the diets of broilers had no detrimental effects ($P > 0.05$) on carcass traits across all measured parameters, including breast, thigh, and wing weights. Despite its general positive influence, the magnitude of the BSFLM effect tends to be moderate on the weight of the breast (SMD = 0.44; 95% CI = −0.49 to 1.37; P_{SMD} = 0.3558, I^2 = 97.8%), and wing (SMD = 0.33; 95% CI = −0.05 to 0.71; P_{SMD} = 0.0906, I^2 = 90.8%). BSFLM, however, only introduces a small effect on the thigh primal cut (SMD = 0.19; 95% CI = −0.34 to 0.72; PSMD = 0.4848; I^2 = 96.2%) of the carcass. This indicates that the inclusion of BSFLM in broiler diets does not compromise carcass yield, suggesting comparable muscle deposition and, consequently, the preservation of commercial value.

Drip, Cook, and Thaw Losses. The summary of the BSFLM inclusion effect on broiler chicken meat quality is presented in Table 2. The estimates from our pooled analysis indicated a consistent reduction in processing losses when BSFLM was included in the broiler birds' diet. BSFLM inclusion had a substantial thawing effect (SMD = −1.55; 95% CI = −3.56 to 0.47; PSMD = 0.1328; I2 = 98.6%) in meat samples compared with the control group. This notwithstanding, BSFLM effect on drip (SMD = −0.42; 95% CI = −1.26 to 0.41; P_{SMD} = 0.3231, I^2 = 96.6%) and cooking (SMD = −0.69; 95% CI = −1.43 to 0.04; P_{SMD} = 0.0653, I^2 = 96.9%) losses were moderate. This improvement may increase processing yield and reduce product shrinkage during storage and cooking, thereby supporting superior juiciness and overall product quality.

Ultimate pH (pHu). The initial meta-analysis, which included all studies for pHu (Supplementary Fig. S2), revealed a non-significant pooled effect size (SMD = 0.25; 95% CI: −0.01 to 0.51; P_{SMD} = 0.0574; I^2 = 84.3%). However, our sensitivity analyses indicated that the study by Pieterse et al. (2019) was highly influential, contributing significantly to the observed pooled effect size and the estimate of heterogeneity. Following its exclusion (Supplementary Fig. S3), the overall effect size decreased in magnitude (SMD = 0.16; 95% CI: −0.05 to 0.36; P_{SMD} = 0.1284), with a reduction in heterogeneity (I^2 = 72.5%). This may signal changes in meat quality, muscle metabolism, and shelf-life, suggesting that the inclusion of BSFLM may alter energy metabolism, resulting in lower glycogen at slaughter and, in turn, reduced post-mortem glycolysis, which may lead to darker, firmer, and water-retentive meat.

Meat Color. The comparative pooled effects of BSFLM on broiler meat color are presented in Table 2. The initial meta-analysis for lightness (L*), which included all studies (Supplementary Fig. S4), revealed a non-significant pooled effect size (SMD = −0.22; 95% CI: −0.62 to 0.17; P_{SMD} = 0.2705; I^2 = 93.0%). However, our Baujat plots and leave-one-out analyses demonstrated that the study by Pieterse et al. (2019.1) was highly influential. After excluding this influential study (Table 2,

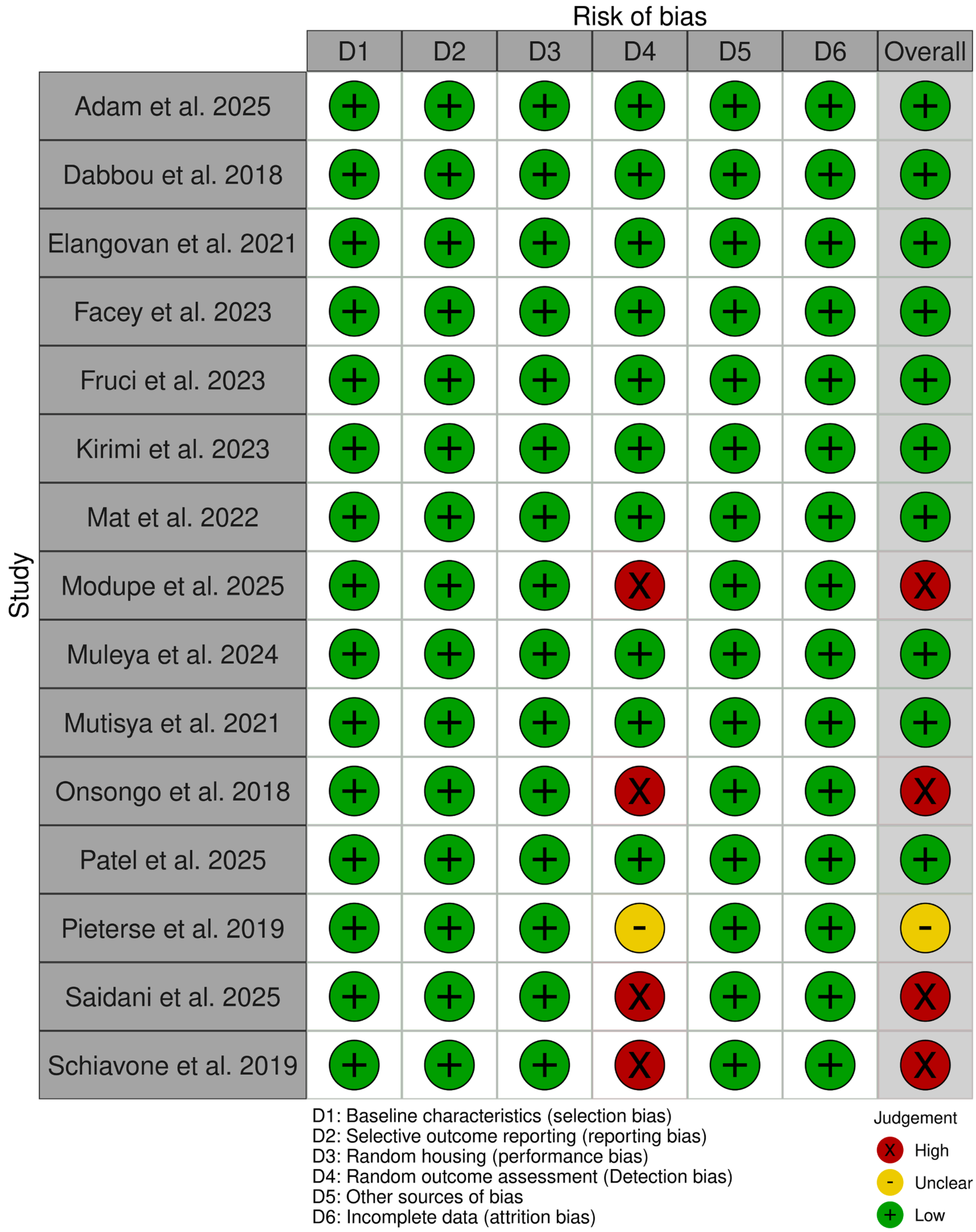

Fig. 3. Traffic light plot showing risk of bias summary of included studies.

Supplementary Fig. 5), the overall effect estimate still suggests that inclusion of BSFLM in the diets of broiler birds generally reduces the lightness of the meat from those broilers (SMD = −0.38; 95% CI: −0.65 to −0.11; P_{SMD} = 0.0067; I^2 = 83.8%).

Similarly, though not significant (P_{SMD} = 0.2514), inclusion of BSFLM reduced yellowness (b*) of meat samples (SMD = −0.53; 95% CI: −1.43 to 0.37; I^2 = 99.3%, initial meta-analysis). Given the dataset's significant publication bias (see Table 3 and Supplementary Fig. 6), bias-corrected analyses using selection models indicated that the adjusted effect size remained largely unchanged (SMD = −0.62; see Table 3), suggesting that publication bias did not alter the core findings. BSFLM inclusion significantly increased the redness (a*) of meat of the treatment group compared to the control (SMD = 0.64; 95% CI: 0.22 to 1.06; P_{SMD} = 0.0029). Our observation of BSFLM's effect in reducing lightness and yellowness while increasing redness is an expected color response to elevated ultimate pH. Therefore, such meat of birds fed BSFLM may be perceived as less fresh by consumers, depending on the market.

Muscle Fat and Ash. Table 2 presents the pooled estimates of BSFLM inclusion effect on broiler meat fat and ash contents. BSFLM-fed broilers showed increased ash (P_{SMD} = 0.4928; SMD = 0.34; 95% CI: −0.64 to 1.32; I^2 = 97.7%) and fat (P_{SMD} = 0.0001; SMD = 0.99; 95% CI: 0.68 to 1.30; I^2 = 72.6%) content. This suggests that BSFLM, naturally rich in lipids and minerals, may have supported the diet-driven nutrient shift in nutrient deposition, carcass composition, and overall meat quality.

Subgroup Analysis and Meta-regression Analysis of Moderate Heterogeneity. Given the moderate heterogeneity observed in the

Table 2
Effect of BSFLM on broiler performance, carcass traits, and meat quality.

Variable	k	Random Effects Model		τ^2	Heterogeneity		
		SMD (95% CI)	P-value		Q	P-value[a]	I^2 (%)
Performance							
ADFI	35	−0.93 (−1.87, 0.01)	0.0514	7.896	1272.26	<0.0001	97.3
ADG	35	0.26 (−0.36, 0.89)	0.4070	3.525	1691.57	<0.0001	98.0
FCR	35	−0.11 (−1.39, 1.17)	0.8695	14.830	3359.84	<0.0001	99.0
Carcass traits							
Breast	17	0.44 (−0.49, 1.37)	0.3558	3.782	728.00	<0.0001	97.8
Thigh	14	0.19 (−0.34, 0.72)	0.4848	0.997	341.67	<0.0001	96.2
Wing	10	0.33 (−0.05, 0.71)	0.0906	0.343	98.11	<0.0001	90.8
Meat quality							
pHu	9	0.16 (−0.05, 0.36)	0.1284	0.072	29.06	0.0003	72.5
Drip loss	6	−0.42 (−1.26, 0.41)	0.3231	1.058	148.44	<0.0001	96.6
Cook loss	7	−0.69 (−1.43, 0.04)	0.0653	0.953	192.57	<0.0001	96.9
Thaw loss	7	−1.55 (−3.56, 0.47)	0.1328	7.339	440.49	<0.0001	98.6
L*	9	−0.38 (−0.65, −0.11)	0.0067	0.149	49.33	0.0067	83.8
a*	10	0.64 (0.22, 1.06)	0.0029	0.427	131.29	<0.0001	93.1
b*	10	−0.53 (−1.43, 0.37)	0.2514	2.078	522.78	<0.0001	98.3
Fat	4	0.99 (0.68, 1.30)	<0.0001	0.071	10.94	0.0121	72.6
Ash	4	0.34 (−0.64, 1.32)	0.4928	0.973	131.41	<0.0001	97.7

Abbreviations: k: number of comparison between BSFLM and control; SMD: Standardized mean difference; I^2: Percentage of total variability attributable to between-study differences; FCR: feed conversion ratio, L*: lightness, a*: redness, b*: yellowness, a: P-value from Cochran's Q test for heterogeneity.

Table 3
Publication bias.

Outcome	Intervention	Egger's test: p-value	Unadjusted effect size (95% CI)	Selection models adjusted effect size (95% CI)	P-value
ADFI	BSFLM	0.0509	-	-	-
ADG	BSFLM	0.0989	-	-	-
FCR	BSFLM	0.6465	-	-	-
Breast	BSFLM	0.7154	-	-	-
Thigh	BSFLM	0.2119	-	-	-
Wing	BSFLM	0.2780	-	-	-
Yellowness	BSFLM	0.0018	−0.53 (−1.43 to 0.37)	−0.62 (−1.63 to 0.39)	0.2301
Redness	BSFLM	0.1376	-	-	-

Abbreviations: FCR: feed conversion ratio, BSFLM: black soldier fly larvae meal.

outcome variables, potential sources of variation across the included studies in the meta-analysis were examined using subgroup and meta-regression analyses. The results of our analyses, categorized by substrate type, processing method, strain, and housing system, are detailed in Tables 4–6 (subgroup analysis) and in Table 7 (meta-regression) for BSFLM inclusion level and feeding duration.

Substrate Type. Subgroup results indicated that BSFLM inclusion significantly varied across all growth responses by substrate type (Table 4). Despite BSFLM derived from non-halal substrates substantially increasing ADG (SMD = 2.22, 95% CI: 0.64 to 3.79), it efficiently reduced the ADFI and FCR (see Table 4) compared to those reared on halal substrates. However, the proportion of between-study variation attributable to substrate type was relatively small (<1%). On the other hand, for carcass primal cuts (breast, thigh, and wing), the effect of BSFLM inclusion in broiler diets did not ($P > 0.05$) vary by the substrate type used in rearing the BSF (Table 5).

Processing Method. The influence of BSFLM on broiler growth (ADG and FCR) varied across processing methods (see Table 4). Although the moderator's account for heterogeneity was relatively low (< 1%), our subgroup analysis revealed that BSFLM processed by oven-drying and sun-drying efficiently reduced FCR of birds, whereas sun-drying increased ADG. Conversely, partially defatted BSFLM moderately reduced ADG. Concerning meat quality characteristics in the included meta-analysis studies, our subgroup analysis (see Table 6) revealed that oven-drying was a significant moderator of the effect of BSFLM on the meta-analysis's ultimate pH ($R^2 = 45.33\%$) and drip loss ($R^2 = 7.69\%$). Again, the effect of BSFLM on thaw loss ($R^2 = 1.10\%$) and yellowness ($R^2 = 2.89\%$) of the meat varied depending on the BSFL processing method.

Housing System. Unlike redness ($P = 0.0217$) and thaw loss ($P = 0.0275$) responses (Table 6), the housing system used to grow the birds did not moderate the influence of BSFLM on growth, carcass primal cuts, and other meat quality characteristics investigated ($P > 0.05$). The meat of birds raised in a battery cage system moderated a pronounced BSFLM effect on redness (SMD = 1.16, $R^2 = 4.01\%$), while deep litter moderated a pronounced reduction effect of BSFLM thaw loss (SMD = −3.01, $R^2 = 1.10\%$).

Strain. Subgroup analysis revealed that a given proportion of the observed heterogeneity in thigh ($R^2 = 6.55\%$), wing ($R^2 = 8.04\%$), and redness ($R^2 = 30.85\%$) is significantly explained by broiler strain (Tables 5 and 6). The moderation, however, varied among the broiler strains. Among these responses, an increased moderation effect was observed in the Cobb 500 strain. In contrast, reduced moderation was observed in Ross 308, suggesting that the bird's genetic background plays a crucial role in how BSFLM drives nutrient shifts toward muscle tissue conversion. This notwithstanding, strain was not a significant moderator of the effect of BSFLM on growth, other carcass, and meat quality traits investigated.

BSFLM inclusion level and feeding duration. The meta-regression analysis evaluating the influence of moderators on the performance, carcass traits, and meat quality of broiler chickens fed BSFLM is presented in Tables 7–9. The results revealed a negative association between the dietary inclusion level of BSFLM and birds' ADFI (slope = −0.0337; $P = 0.0290$), with the model accounting for 11.27% of the between-study variation in ADFI. At a mean inclusion level of 28%, BSFLM was associated with a reduction in ADFI of approximately 0.93 standard deviations relative to the control cohort (Table 7). When evaluated alongside the global FCR average (Table 2), this reduced ADFI indicates that birds receiving the BSFLM diet exhibited distinct nutrient-utilization dynamics, maintaining comparable performance metrics despite lower feed intake. Concurrently, linear declines were observed in the meat thaw loss (slope = −0.0702; $P < 0.0001$, $R^2 = 85.34\%$) and yellowness (slope = −0.2446; $P = 0.0068$, $R^2 = 41.95\%$) (see Table 9). Regarding broader meat quality parameters, our model demonstrated that the BSFLM inclusion level accounted for 25.52% of the observed heterogeneity in meat redness, indicating a direct, dose-dependent relationship. The inclusion level of BSFLM in our meta-regression model, however, was not a significant ($P > 0.05$) predictor of the

Table 4
Subgroup analysis showing the effects of BSFLM on broiler performance.

Variable	Subgroup	NC	Random Effects Model						R² (%)
			SMD (95% CI)	I^2 (%)	τ^2	d.f	Q	[a]P-value	
ADFI									
Substrate type	Halal	20	−0.01 (−0.31, 0.29)	92.9	0.45	1	4.23	0.0398	0.43
	Non-halal	7	−0.41 (−8.58, −0.23)	98.9	31.43				
Processing method	Oven-dried	13	−0.77 (−2.96, 1.43)	97.6	16.11	3	5.46	0.1409	0.43
	Partially defatted	14	−0.32 (−0.60, −0.03)	93.6	0.27				
	Sun-dried	4	−4.39 (−7.92, −0.86)	98.8	12.80				
	Defatted	3	−0.60 (−1.60, 0.40)	96.7	0.75				
Housing system	Deep-litter	30	−1.09 (−2.18, 0.01)	97.6	9.21	1	1.16	0.2807	0.09
	Metabolic cage	4	−0.41 (−0.98, 0.17)	91.7	0.32				
Strain	Cobb 500	17	−1.86 (−3.78, 0.07)	98.3	16.22	3	7.41	0.0599	0.59
	Ross 308	6	0.27 (−0.28, 0.83)	92.9	0.45				
	Ross x Ross 708	8	−0.46 (−0.92, −0.00)	96.2	0.42				
	Vencobb 400	3	−0.05 (−0.31, 0.20)	0	0				
ADG									
Substrate type	Halal	20	−0.24 (−0.99, 0.50)	97.9	2.82	1	7.70	0.0055	0.57
	Non-halal	7	2.22 (0.64, 3.79)	97.6	4.42				
Processing method	Oven-dried	13	0.46 (−0.08, 1.00)	95.9	0.93	3	19.45	0.0002	1.15
	Partially defatted	14	−0.29 (−0.57, −0.02)	92.2	0.25				
	Sun-dried	4	3.46 (1.50, 5.42)	98.0	3.90				
	Defatted	3	−2.18 (−6.85, 2.49)	99.7	16.94				
Housing system	Deep-litter	30	0.35 (−0.38, 1.07)	98.2	4.02	1	2.73	0.0986	0.16
	Metabolic cages	4	−0.47 (−1.10, 0.17)	93.2	0.40				
Strain	Cobb 500	17	0.59 (−0.67, 1.84)	98.8	6.91	3	7.51	0.0572	0.44
	Ross 308	6	0.40 (−0.33, 1.12)	95.8	0.79				
	Ross x Ross 708	8	−0.43 (−0.82, −0.04)	94.8	0.30				
	Vencobb 400	3	0.13 (−0.13, 0.38)	0	0				
FCR									
Substrate type	Halal	20	0.78 (−0.76, 2.32)	98.2	12.33	1	6.92	0.0085	0.43
	Non-halal	7	−3.50 (−6.30, −0.71)	98.4	14.04				
Processing method	Oven-dried	13	−0.44 (−0.87, −0.01)	93.3	0.59	3	15.26	0.0016	0.45
	Partially defatted	14	1.69 (−0.80, 4.18)	99.5	22.51				
	Sun-dried	4	−5.80 (−9.25, −2.36)	98.8	12.13				
	Defatted	3	0.54 (−0.48, 1.57)	96.8	0.80				
Housing system	Deep-litter	30	−0.78 (−1.84, 0.27)	98.9	8.59	1	2.61	0.1065	0.08
	Metabolic cages	4	4.95 (−1.93, 11.82)	99.6	49.01				
Strain	Cobb 500	17	−1.41 (−2.82, −0.00)	98.0	8.72	3	7.76	0.0513	0.23
	Ross 308	6	−0.30 (−0.98, 0.39)	95.3	0.71				
	Ross x Ross 708	8	3.40 (−0.62, 7.41)	99.7	33.45				
	Vencobb 400	3	−1.48 (−2.71, −0.24)	94.8	1.11				

NC: Number of comparisons between electrical stunning and halal slaughter; SMD: Standardized mean difference; I^2: Percentage of total variability attributable to between-study differences; τ^2: Estimated variance of the true effect sizes across subgroups; d.f: degree of freedom; Q: X^2 statistics; R^2: the amount of heterogeneity accounted for by the covariate (moderator); a = P-value for the test of differences between subgroups.

observed between-study variation in ADG and FCR (see Table 7), thigh and wing (see Table 8), and ultimate pH and drip loss (see Table 9).

Our meta-regression models further indicated that feeding duration of BSFLM to broilers explained a significant proportion of the observed heterogeneity in ADG ($R^2 = 14.83\%$), drip loss ($R^2 = 69.99\%$), thaw loss ($R^2 = 33.55\%$), and meat redness ($R^2 = 62.84\%$). At a centered feeding duration of 37 days, BSFLM favored broiler growth, maintaining an ADG of 0.26 standard deviations higher than the control group. These findings suggest that BSFLM's potential growth benefit in broilers may be realized with long-term feeding (beyond the 21-day growth-out phase). However, extending feeding duration beyond 37 days could reduce thaw loss ($P \leq 0.05$) and improve redness, but increase drip loss in broiler meat (see Table 9).

Discussion

Black soldier fly larvae have emerged as a subject of considerable interest in sustainable animal nutrition, primarily due to their favorable nutrient profile and demonstrated benefits for growth performance and health outcomes in livestock (Dabbou et al., 2021; NRC, 1994). As a novel protein source, BSFLM offers potential to reduce reliance on conventional feed ingredients, aligning with broader goals of environmental sustainability and resource efficiency. Despite the expanding body of literature supporting its application in broiler diets, critical knowledge gaps persist regarding the factors that modulate its bioactivity and physiological effects (Sjofjan et al., 2025). The present meta-analysis sought to synthesize available evidence on the impact of BSFLM inclusion in broiler nutrition, with specific attention to performance indices, carcass characteristics, and meat quality parameters. A distinctive aspect of this investigation was the consideration of the origin of the rearing substrate, classified as halal or non-halal, as a potential determinant of nutritional efficacy.

Growth Performance

This meta-analysis supports the trend noted by Chhetri et al. (2025), Nayohan et al. (2022), Martínez Marín et al. (2023), and Hayat et al. (2024), all of whom observed decreases in ADFI and FCR in broilers fed BSFLM-based feeds. However, unlike Nayohan et al., Martínez Marín et al., and Hayat et al., who applied a mixed-model procedure, our results are closer to those of Chhetri et al., indicating that BSFLM can increase BWG. However, results vary widely across studies due to differences in larval substrate, processing methods, feed inclusion rates, and feeding duration (see Tables 4 and 7).

These factors may have introduced a diverse nutrient profile in BSFLM, thereby partly reducing the digestibility of essential amino acids in such diets and, in turn, reducing net protein utilization (Brede et al., 2018; Hartinger et al., 2021; Neumann et al., 2018). When conventional

Table 5
Subgroup analysis showing the effects of BSFLM on broiler carcass traits.

			Random Effects Model						
Variable	Subgroup	NC	SMD (95% CI)	I^2 (%)	τ^2	d.f	Q	[a]p-value	R^2 (%)
Breast									
Substrate type	Halal	9	−0.20 (−1.62, 1.23)	98.0	4.69	1	0.45	0.5025	0.09
	Non-halal	4	0.40 (−0.62, 1.43)	95.8	1.05				
Processing method	Sun-dried	4	0.40 (−0.62, 1.43)	95.8	1.05	2	0.51	0.7746	0.07
	Oven-dried	9	0.79 (−0.21, 1.78)	97.6	2.27				
	Partially defatted	3	−0.61 (−5.45, 4.23)	99.4	18.19				
Housing system	Deep-litter	14	0.64 (−0.47, 1.75)	97.8	4.43	1	3.48	0.0620	0.48
	Battery cage	3	−0.49 (−0.90, −0.08)	80.1	0.10				
Strain	Cobb 500	10	0.73 (−0.25, 1.70)	97.8	2.41	1	0.24	0.6248	0.06
	Ross 308	3	0.48 (0.29, 0.67)	0	0				
Thigh									
Substrate type	Halal	9	−0.02 (−0.64, 0.59)	96.0	0.86	1	1.88	0.1700	0.60
	Non-halal	4	0.86 (−0.24, 1.95)	96.3	1.20				
Processing method	Sun-dried	4	0.86 (−0.24, 1.95)	96.3	1.20	2	2.03	0.3627	0.65
	Oven-dried	6	0.21 (−0.32, 0.74)	93.4	0.41				
	Partially defatted	3	−0.50 (−2.10, 1.11)	98.1	1.96				
Housing system	Deep-litter	11	0.04 (−0.60, 0.68)	96.3	1.14	1	2.46	0.1166	0.72
	Battery cage	3	0.73 (0.16, 1.30)	89.3	0.23				
Strain	Cobb 500	7	0.80 (0.18, 1.42)	94.0	0.66	1	11.35	0.0008	6.55
	Ross 308	3	−0.32 (−0.51, −0.13)	0	0				
Wing									
Substrate type	Halal	6	0.17 (−0.21, 0.55)	87.7	0.20	1	0.83	0.3616	0.85
	Non-halal	4	0.58 (−0.21, 1.36)	93.8	0.60				
Processing method	Sun-dried	4	0.58 (−0.21, 1.36)	93.8	0.60	1	0.83	0.3616	0.85
	Oven-dried	6	0.17 (−0.21, 0.55)	87.7	0.20				
Housing system	Deep-litter	7	0.25 (−0.26, 0.77)	92.1	0.45	1	0.48	0.4885	0.49
	Battery cage	3	0.50 (0.01, 1.00)	86.2	0.16				
Strain	Cobb 500	7	0.54 (0.09, 1.00)	90.4	0.35	1	7.89	0.0050	8.04
	Ross 308	3	−0.17 (−0.36, 0.03)	5.40	0.00				

NC: Number of comparisons between electrical stunning and halal slaughter; SMD: Standardized mean difference; I^2: Percentage of total variability attributable to between-study differences; τ^2: Estimated variance of the true effect sizes across subgroups; d.f: degree of freedom; Q: X^2 statistics; R^2: the amount of heterogeneity accounted for by the covariate (moderator); a = P-value for the test of differences between subgroups.

protein sources are replaced with BSFLM on a protein or weight basis, the resulting amino acid balance may not meet animal requirements, sometimes hindering growth performance (Martínez Marín et al., 2023). Accordingly, in broiler nutrition, such a sensitive scenario may reduce intake when nutrient density or palatability changes (Roura et al., 2013; Yoshida et al., 2015). The consistent ADFI-reducing effect of BSFLM could suggest a shift in diet palatability and bulk properties. Feed odor and taste significantly influence chickens' feed choices and consumption rates (Yoshida et al., 2018). Marono et al. (2015, 2017) noted that increasing BSFLM alters feed color and introduces new odors, prompting broilers to reject the feed. In addition, a plausible explanation for the depressed feed intake may be chitin. This fibrous polysaccharide can act as an antinutritional factor at high concentrations, thereby influencing protein digestibility (Bovera et al., 2016). Previous studies have similarly reported that chitin in BSFLM affects feed acceptability and protein digestibility in broiler chickens (Cutrignelli et al., 2018; Dabbou et al., 2021; Longvah et al., 2011; Sánchez-Muros et al., 2014). Likewise, the elevated fat content in higher BSFLM diets could have increased the diet's energy density, thereby enhancing its overall energy value through the extra caloric effect of dietary lipids (Attia et al., 2023). Consequently, birds may have satisfied their energy requirements with reduced feed consumption.

Despite the observed reduction in intake, BSFLM is inclined to improve broiler ADG and FCR. The high biological value of BSFLM protein and its favourable amino acid profile may have partially offset the bird's reduced intake by improving nutrient utilization efficiency. The present meta-analysis revealed that broilers fed BSFLM derived from non-halal substrates exhibited superior ADG and FCR (see Table 4), which may be associated with differences in substrate composition rather than halal status alone. Non-halal substrates, such as slaughterhouse waste or animal by-products, typically contain higher concentrations of protein and lipids than halal vegetable-based wastes (Naser El Deen et al., 2023; Barragan-Fonseca et al., 2019; Gold et al., 2020). However, this observation should be interpreted with caution, as substrate classification (halal versus non-halal) is inherently linked to substrate origin and nutritional composition, and may therefore reflect underlying nutrient differences rather than halal status per se. Such variation can influence larval nutrient accumulation, with black soldier fly larvae raised on animal-based (haram/prohibited) feeds showing a more favourable nutrient profile than those raised on vegetables (Fitriana et al., 2022).

Similarly, the way black soldier fly larvae are processed alters their biological activity and their impact on physiological functions (Sjofjan et al., 2025). Methods such as oven-drying, sun-drying, and, to a lesser degree, defatting seem most effective at maintaining or improving nutrient availability in black soldier fly larvae, as shown in Table 4. The relatively mild thermal conditions associated with oven- and sun-drying may have reduced moisture content and better preserved heat-sensitive nutrients, such as medium-chain fatty acids (MCFAs) and bioactive peptides, which play critical roles in immune and metabolic regulation (Sjofjan et al., 2025; Muthee et al., 2024). Compared with high-temperature processing, these approaches may better maintain protein integrity, thereby avoiding the extensive denaturation, breakdown, and volatilization observed at higher heat-treatment temperatures (Baek et al., 2019; Manditsera et al., 2022; Ochieng et al., 2022). Sun-drying may also boost vitamin D production in larvae through UV exposure, which could benefit birds' bone development and metabolism (Liu et al., 2017; Oonincx et al., 2016, 2018).

Our meta-analysis also reveals a clear temporal divergence between short- and long-term responses in broilers fed BSFLM-based diets (Table 7), with performance advantages being more pronounced during the early feeding period. The diminishing marginal utility of BSFLM under prolonged feeding may be linked to cumulative chitin intake. Although broilers possess endogenous chitinase activity, the persistence of partially undigested chitin in the gastrointestinal tract over time may elevate digesta viscosity. An increased load of undigested material in the

Table 6
Subgroup analysis showing the effects of BSFLM on broiler meat quality.

Variable	Subgroup	NC	Random Effects Model						R^2 (%)
			SMD (95% CI)	I^2 (%)	τ^2	d.f	Q	[a]p-value	
pHu									
Processing method	Oven-dried	5	0.37 (0.16, 0.59)	54.3	0.03	1	12.17	0.0005	45.33
	Partially defatted	3	−0.15 (−0.35, 0.05)	0.0	0.0				
Housing system	Deep-litter	7	0.09 (−0.14, 0.33)	71.6	0.07	1	2.04	0.1536	7.02
	Battery cage	2	0.39 (0.05, 0.73)	56.6	0.03				
Strain	Cobb 500	2	0.39 (0.05, 0.73)	56.6	0.03	1	0.01	0.9110	0.11
	Ross 308	3	0.36 (0.02, 0.71)	68.8	0.06				
Drip loss									
Processing method	Oven-dried	3	−1.24 (−2.14, −0.35)	94.4	0.59	1	11.41	0.0007	7.69
	Partially defatted	3	0.40 (0.08, 0.72)	60.0	0.05				
Cook loss									
Processing method	Oven-dried	3	−1.02 (−2.67, 0.63)	98.6	2.08	1	0.91	0.3400	0.54
	Partially defatted	3	−0.19 (−0.66, 0.28)	81.4	0.14				
Housing system	Deep-litter	4	−0.45 (−1.06, 0.15)	94.0	0.36	1	0.41	0.5242	0.21
	Battery cage	3	−1.02 (−2.67, 0.63)	98.6	2.08				
Thaw loss									
Processing method	Sun-dried	4	−3.01 (−5.63, −0.40)	98.5	7.02	1	4.86	0.0275	1.10
	Oven-dried	3	0.39 (−1.13, 1.90)	98.2	1.76				
Housing system	Deep-litter	4	−3.01 (−5.63, −0.40)	98.5	7.02	1	4.86	0.0275	1.10
	Battery cage	3	0.39 (−1.13, 1.90)	98.2	1.76				
Lightness (L)									
Processing method	Oven-dried	5	−0.28 (−0.56, −0.00)	72.9	0.08	1	0.15	0.6955	0.35
	Partially defatted	3	−0.44 (−1.21, 0.32)	92.6	0.42				
Housing system	Deep-litter	7	−0.39 (−0.75, −0.02)	87.7	0.21	1	0.01	0.9133	0.02
	Battery cage	2	−0.36 (−0.58, −0.14)	0	0				
Strain	Cobb 500	2	−0.36 (−0.58, −0.14)	0	0	1	0.22	0.6357	1.49
	Ross 308	3	−0.23 (−0.73, 0.27)	85.2	0.17				
Redness (a)									
Processing method	Oven-dried	6	0.56 (−0.01, 1.13)	94.2	0.48	1	0.54	0.4620	0.44
	Partially defatted	3	0.94 (0.09, 1.79)	93.3	0.53				
Housing system	Deep-litter	7	0.41 (−0.08, 0.90)	91.6	0.40	1	5.27	0.0217	4.01
	Battery cage	3	1.16 (0.74, 1.59)	79.0	0.11				
Strain	Cobb 500	3	1.16 (0.74, 1.59)	79.0	0.11	1	26.54	<0.0001	30.85
	Ross 308	3	−0.05 (−0.24, 0.14)	0	0				
Yellowness (b)									
Processing method	Oven-dried	6	−0.01 (−0.91, 0.89)	97.3	1.24	1	11.73	0.0006	2.89
	Partially defatted	3	−2.10 (−2.89, −1.32)	90.3	0.43				
Housing system	Deep-litter	7	−0.74 (−1.77, 0.29)	98.2	1.90	1	0.37	0.5407	0.07
	Battery cage	3	−0.03 (−2.05, 1.99)	98.9	3.15				
Strain	Cobb 500	3	−0.03 (−2.05, 1.99)	98.9	3.15	1	0.00	0.9684	0.00
	Ross 308	3	0.01 (−0.18, 0.20)	0	0				

NC: Number of comparisons between electrical stunning and halal slaughter; SMD: Standardized mean difference; I^2: Percentage of total variability attributable to between-study differences; τ^2: Estimated variance of the true effect sizes across subgroups; d.f: degree of freedom; Q: X^2 statistics; R^2: the amount of heterogeneity accounted for by the covariate (moderator); a = P-value for the test of differences between subgroups.

Table 7
Meta-regression showing the effects of BSFLM on broiler performance.

Variable	Test of Moderators		Mixed-Effects Model Estimate		
	QM [df]	P-value	*Intercept [SE]	Slope [SE]	R^2 (%)
ADFI					
Inclusion level	4.7649 [1]	0.0290	−0.9307 [0.4505]	−0.0337 [0.0154]	11.27
Feeding duration	0.0023 [1]	0.9618	−0.9330 [0.4862]	0.0028 [0.0585]	0.00
ADG					
Inclusion level	2.2056 [1]	0.1375	0.2664 [0.3146]	0.0160 [0.0108]	3.05
Feeding duration	6.8338 [1]	0.0089	0.2656 [0.2951]	−0.0929 [0.0356]	14.83
FCR					
Inclusion level	1.5328 [1]	0.2157	−0.1021 [0.6478]	0.0276 [0.0223]	1.54
Feeding duration	1.9390 [1]	0.1638	−0.1090 [0.6439]	0.1080 [0.0776]	2.71

SE: standard error; QM: Q-statistics for moderators; R^2: percentage of heterogeneity accounted for by the moderator; FCR: feed conversion ratio.
Slope: represents the rate of change in the moderator.
* = Centred intercept.

Table 8
Meta-regression showing the effects of BSFLM on broiler carcass traits.

Variable	Test of Moderators		Mixed-Effects Model Estimate		
	QM [df]	P-value	*Intercept [SE]	Slope [SE]	R^2 (%)
Thigh					
Inclusion level	1.2911 [1]	0.2558	0.1915 [0.2687]	0.0106 [0.0094]	2.03
Feeding duration	0.1353 [1]	0.7130	0.1899 [0.2809]	0.0191 [0.0519]	0.00
Wing					
Inclusion level	0.0190 [1]	0.8905	0.3282 [0.2055]	−0.0009 [0.0064]	0.00
Feeding duration	2.0465 [1]	0.1526	0.3269 [0.1832]	0.0480 [0.0335]	11.67

SE: standard error; QM: Q-statistics for moderators; R^2: percentage of heterogeneity accounted for by the moderator.
Slope: represents the rate of change in the moderator.
* = Centred intercept.

distal small intestine can stimulate bacterial proliferation, which subsequently alters gut morphology, reduces lipid absorption efficiency, and increases endogenous fat losses (Chang et al., 2023; Smulikowska

Table 9
Meta-regression showing the effects of BSFLM on selected broiler breast muscle indices.

Variable	Test of Moderators		Mixed-Effects Model Estimate		
	QM [df]	P-value	*Intercept [SE]	Slope [SE]	R^2 (%)
pHu					
Inclusion level	0.0001 [1]	0.9931	0.1594 [0.1123]	−0.0003 [0.0330]	0.00
Feeding duration	1.4610 [1]	0.2268	0.1585 [0.1027]	−0.0195 [0.0162]	5.61
Drip loss					
Inclusion level	0.2195 [1]	0.6394	−0.4217 [0.4645]	0.0584 [0.1246]	0.00
Feeding duration	11.4646 [1]	0.0007	−0.4190 [0.2419]	0.1170 [0.0346]	69.99
Thaw loss					
Inclusion level	32.4683 [1]	<0.0001	−1.5589 [0.4060]	−0.0702 [0.0123]	85.34
Feeding duration	3.9919 [1]	0.0457	−1.5508 [0.8414]	−0.4847 [0.2426]	33.55
Redness					
Inclusion level	3.8440 [1]	0.0499	0.6395 [0.1864]	0.0940 [0.0480]	25.52
Feeding duration	13.5643 [1]	0.0002	0.6363 [0.1371]	0.0802 [0.0218]	62.84
Yellowness					
Inclusion level	7.3220 [1]	0.0068	−0.5281 [0.3522]	−0.2446 [0.0904]	41.95
Feeding duration	1.4341 [1]	0.2311	−0.5286 [0.4493]	−0.0854 [0.0713]	4.51

SE: standard error; QM: Q-statistics for moderators; R^2: percentage of heterogeneity accounted for by the moderator.
Slope: represents the rate of change in the moderator.
* = Centred intercept.

et al., 2002). These physiological shifts suggest that BSFLM may be more effectively utilized within a phase-feeding strategy, where inclusion levels are adjusted according to developmental stage, rather than through fixed inclusion rates applied uniformly across the production cycle.

Carcass traits

The present meta-analysis further indicates that the anabolic response to BSFLM protein is ultimately constrained by the bird's genetic ceiling for muscle development (Tables 2 and 5). The observed increases in high-value carcass cuts could have been driven primarily by the superior ileal digestibility of limiting amino acids, particularly lysine and threonine (Shelomi, 2020; Lu et al., 2022; Attia et al., 2023), which provide the essential substrates for myofibrillar protein synthesis. Beyond amino acid supply, the distinct lipid fraction of BSFLM, dominated by lauric acid, may function as a metabolic signal that supports skeletal muscle hypertrophy (Wei et al., 2026). Medium-chain fatty acids, such as lauric acid, have been shown to enhance IGF-1 synthesis by improving nutrient availability, reducing the inflammatory load, and modulating endocrine pathways (Gomez-Osorio et al., 2021; Kareem et al., 2016). Prior studies in broilers have linked IGF-1 expression to improved muscle growth, feed efficiency, and overall productivity (Chen et al., 2022; Saxena et al., 2020). However, the sustained translation of these nutritional and metabolic signals into muscle mass remains ultimately limited by the bird's inherent genetic potential for protein deposition.

Meat quality

The trend toward increased muscle fat in BSFLM-fed broilers likely reflects the intrinsic lipid profile of the larvae, which is shaped by factors such as substrate composition, larval diet, and rearing conditions (Danieli et al., 2019; Janssen et al., 2017). This aligns with evidence that BSFL are highly efficient at bioaccumulating dietary fats from their substrates (Keshaini et al., 2025). As noted by Tomberlin et al. (2002), the substantial fat reserves accumulated during the prepupal stage play a critical biological role in supporting daily growth, mating activity, and reproduction. This observation cannot be separated from the consequences of meat quality development.

The inclusion of BSFLM in broiler diets appears to exert notable effects on postmortem muscle biochemistry, particularly through its association with elevated ultimate pH (pHu). A higher pHu has been consistently linked to improved water-holding capacity, thereby reducing drip, thaw, and cooking losses, which collectively enhance meat quality attributes such as juiciness and yield (Lancaster et al., 2020). Mechanistically, elevated pHu is thought to preserve myofibrillar integrity and limit protein denaturation, thereby maintaining the structural capacity of muscle fibers to retain water. This phenomenon may be influenced by glycogen availability at slaughter, as reduced glycogen reserves limit postmortem glycolysis and acidification, resulting in higher pHu values (Bendall, 1973). In turn, restricted oxygen diffusion within high-pHu muscle favors the accumulation of deoxymyoglobin and metmyoglobin, pigments that impart a darker appearance to meat (Mancini and Hunt, 2005). While such chromatic changes may affect consumer perception, Kotula and Wang (1994) reported that glycogen content at slaughter in chickens influenced pHu without substantially altering color or expressible moisture. Taken together, these findings suggest that including BSFLM may modulate muscle energy metabolism to improve functional quality. However, the extent of its impact on sensory traits remains to be fully elucidated.

While this meta-analysis provides insight into the nature of the effects of variability in BSFLM rearing substrates, the following caveats highlight potential limitations of the study. By applying a conventional rather than a multi-level meta-analytic framework, within-study correlation structures may not have been adequately accounted for; could have led to underestimation of standard errors and confidence intervals. Since our study has fewer subgroups for some of the moderators tested, the results of the subgroup analysis should be interpreted with caution.

In conclusion, this meta-analysis indicates that BSFLM is a highly viable and sustainable protein alternative for the broiler industry, with potential to replace conventional feed ingredients such as soybean meal without adversely affecting growth performance, carcass traits, or meat quality. BSFLM can improve water-holding capacity, an effect linked to a higher ultimate pH that benefits juiciness and processing yield while shifting meat toward redder and darker coloration. Among processing methods, oven-drying and sun-drying proved most effective for preserving nutrient integrity. The origin of the rearing substrate appears to be associated with differences in larval nutritional quality and observed performance outcomes, with broilers fed BSFLM derived from non-halal substrates showing comparatively higher growth performance. Notably, at an average inclusion of 28% fed over an extended duration (37 days), BSFLM can maintain or improve ADG while efficiently reducing FCR in broiler birds. Overall, BSFLM offers a promising pathway toward sustainability in poultry production, provided that producers carefully consider substrate choice, bird genetics, and processing techniques to meet both nutritional and market requirements.

CRediT authorship contribution statement

Utibe Mfon Okon: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Emmanuel Nuamah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Muhammad Nizam Hayat:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Mohd Amran Mohd Radzi:** Writing – review & editing, Supervision, Methodology. **Azalea Hani Othman:** Writing – review & editing, Supervision, Methodology.

Awis Qurni Sazili: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Disclosures

The authors declare that they have no known conflicts of interest that could have influenced the work reported in this paper.

Acknowledgements

The author, Utibe Mfon Okon, sincerely appreciates the Malaysian Ministry of Higher Education's sponsorship of his studies in Malaysia. Emmanuel Nuamah (Jeonbuk National University, South Korea) is acknowledged for his substantial contribution to this study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.psj.2026.107379.

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