

Dietary Oil Type and Late Feed Restriction Elicit Synergistic Effects on Growth, Caeca Bacteria, Carcass, Fat Accretion, and Muscle Lipids in Female Broilers

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The influence of dietary oil type (OT) and late feed restriction (FR) on growth, caeca bacteria count, carcass, separable fat depots, serum and muscle lipids, and meat quality in broilers is examined. In total, 224, 21-day-old female Arbor acres broilers are randomly allotted to either PN, Unrestricted+50 g kg⁻¹ palm oil (PO); PR, 25%-FR+PO; SN, Unrestricted+50 g kg⁻¹ soybean oil (SO); or SR, 25%-FR+SO for 21 d. The SN and PR birds have the heaviest and lightest body weight gain (BWG), respectively. Feed conversion ratio (FCR) is poorer in the PN birds. Feed-restricted birds have more caeca *Lactobacillus* and lower *Salmonella*, serum cholesterol, and triglycerides. Carcass yield is higher in SR birds and lower in PN birds. The FR-OT interaction is significant for muscle lipids and weight of fat depots. The PN birds deposit more abdominal, intramuscular, sartorial, mesentery and neck fats, muscle saturated fatty acids, and C18:1n-9 and lower C18:3n-3 and C20:5n-3 than other birds. Neither OT nor FR affects the pH, color, water holding capacity, and oxidative stability of breast meat. The changes elicited by 25%-FR on BWG, FCR, carcass yield, depot fats, and muscle lipids in female broilers are dependent on dietary OT.

Practical Application: Fast growth rate and unrestricted access to feed can predispose broiler chickens to excessive fat accretion, which is counterproductive. Producing high-quality carcasses that meet consumers' expectation is crucial for sustainable and efficient broiler production. The possible interaction between dietary OT and late quantitative FR in mitigating excessive fat accretion and altering production indices in female broilers is explored. Late quantitative FR reduces BWG, FCR, serum lipids, caeca pH and *Salmonella* spp. and fat accretion in fat depots, and enhances carcass yield and caeca *Lactobacillus* spp. However, the impacts are more pronounced in the PO birds than the SO birds. Late FR improves the C18:3n-3 and C18:2n-6 contents in PO meat while reducing the C14:0 and C16:0 contents in SO meat. These findings explicate that dietary OT and late quantitative FR can be synergistically used to mitigate excessive fat accretion and alter growth, caeca microflora, and muscle lipids in broilers.

1. Introduction

The fast growth rate in the modern-day broiler chickens has raised health,^[1,2] productivity,^[3,4] and welfare^[5-7] concerns, in addition to increased fat accretion.^[3,8,9] Excessive fat accretion is counterproductive because it has no commercial value,^[3,8] reflects ineffective utilization of dietary energy and poor feed efficiency,^[8,10,11] reduces carcass yield and quality and produces high-fat meat that is not in sync with the prevailing consumers' expectation in recent times.^[3,8,11]

Unrestricted access to feed could predispose broiler chickens to excessive fat accretion.^[3,8] Consequently, various feed restriction (FR) strategies have been deployed to mitigate excessive fat accretion in broilers.^[3,12,13] However, FR-induced complications such as boredom, overdrinking, feeding frustration, chronic hunger, and increased aggression, that could constitute animal welfare concerns abound.^[14-17] The severity of these problems is more in young birds owing to the high metabolic requirements associated with rapid growth rate at this stage.^[17,18] Therefore, applying FR strategies at finisher phase may alleviate the aforementioned problems in broilers. Besides, extensive fat accretion in broilers ensues at the finisher phase.^[19] Thus, it is probable that quantitative FR at finisher phase would exert profound impact on fat accretion in broiler chickens.

The high caloric density of oils and fats has made them ideal candidates to meet the energy requirements of fast-growing broiler

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chickens at a low cost.^[20–22] Dietary oils enhance nutrient absorption, feed efficiency, and palatability.^[23–25] Moreover, dietary oils could exert a marked impact on fat accretion in broiler chickens depending on the degree of saturation, chain length, and level of dietary oils^[23–26] as well as sex, strain, and age of birds.^[27,28] Since oil supplementation and FR are common practices in broiler production, it is plausible to speculate a synergy between dietary oil type (OT) and late FR on fat accretion in broiler chickens. In addition, information regarding the influence of interactions between dietary oils and FR on fat accretion in broilers is, to our knowledge, very limiting. Therefore, this study aimed at assessing the impact of dietary OT and late quantitative FR on growth, serum lipids, caeca bacterial counts, carcass traits, separable fat depots, muscle lipids, and meat quality in female broiler chickens.

2. Experimental Section

The trial was carried out following the guidelines approved (FERC/ASN/2017/154) by the Animal Ethics and Use Committee, University of Ilorin.

2.1. Birds, Diets, and Management

In total, 224, 21-day-old female Arbor acres broiler chickens (BW, 805 ± 25) were randomly allotted to one of the four treatment groups, namely, PN, Unrestricted + 50 g kg⁻¹ Palm oil (PO); PR, 25%-FR (Restricted) + 50 g kg⁻¹ PO; SN, Unrestricted + 50 g kg⁻¹ Soybean oil (SO); or SR, Restricted + 50 g kg⁻¹ SO for 21 d. Each treatment group had seven replicates with eight chickens/replicate. Chickens were raised on floor pens. Finisher diets were formulated (Table 1) according to Arbor Acres Aviagen, and National Research Council (NRC)^[29] guidelines and were offered as mash. Clean water was provided ad libitum throughout the trial. The unrestricted birds had free access to feed. The amount of feed offered was adjusted daily to account for changes in body weight (BW). On each day, feed left-over was always present in the feeding troughs of the unrestricted birds. The 25% FR was achieved by supplying 75% of the recommended feed intake (Arbor Acres Aviagen guideline) to the restricted birds. Feed chemical composition was determined by the AOAC^[30] method. Dry matter was determined by oven drying at 105 °C to constant weight. Crude protein (N*6.25) was determined by the Kjeldahl method after acid digestion. Ether extract was determined by the petroleum ether-extraction method using a Soxhlet apparatus. Ash was determined by incineration at 550 °C for 6 h.

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Table 1. Ingredients, chemical composition, and fatty acid composition of dietary treatments and oils.

Feed ingredient [g kg ⁻¹]	Dietary treatment		Palm oil	Soybean oil
	PO	SO		
Corn	533	533		
Groundnut cake	180	180		
Soybean meal (44%)	140	140		
Maize offal	30.0	30.0		
Wheat bran	30.0	30.0		
Fishmeal (68%)	10.0	10.0		
Palm oil	50.0			
Soybean oil		50.0		
Oyster shell	8.00	8.00		
Limestone	4.00	4.00		
Dicalcium phosphate	5.00	5.00		
¹ Mineral-vitamin premix	2.50	2.50		
Salt	2.50	2.50		
Lysine	3.00	3.00		
Methionine	2.50	2.50		
Analyzed composition [g kg ⁻¹]				
Dry matter	925	926		
Crude protein	211	211		
Ether extract	75.0	75.0		
Crude fiber	40.4	40.5		
Ash	35.9	35.8		
Calculated analysis				
Metabolizable energy [kcal kg ⁻¹]	3150	3150		
Available phosphorus	5.66	5.66		
Calcium	10.8	10.8		
Lysine	12.8	12.8		
Methionine	6.50	6.50		
Fatty acids (% total fatty acid)				
C12:0	0.33	0.04	0.36	0.00
C14:0	0.76	0.09	1.05	0.02
C16:0	32.4	11.6	37.4	11.2
C16:1n-7	0.18	0.10	0.22	0.07
C18:0	3.80	4.30	4.20	4.11
C18:1n-9	39.1	24.6	44.40	25.0
C18:2 n-6	22.5	53.2	12.10	52.8
C18:3 n-3	1.20	6.06	0.27	6.70

Note: PO, palm oil; SO, soybean oil. ¹Supplied per kg diet: cholecalciferol 43.8 µg; α-tocopherol 26.8 mg; thiamine 1.43 mg; retinol 3.45 mg; riboflavin 3.44 mg; niacin 40.17 mg; pyridoxine 2.29 mg; pantothenic acid 6.46 mg; folic acid 0.56 mg; biotin 0.05 mg; menadione 2.29 mg; cyanocobalamin 0.05 mg; zinc 120 mg; iron 120 mg; manganese 150 mg; copper 15 mg; selenium 0.3 mg; iodine 1.5 mg; cobalt 0.4 mg.

2.2. Data Collection

Feed intake and body weight records were taken weekly, and the data were used to calculate body weight gain (BWG) and feed conversion ratio (FCR). On day 20, blood samples were collected from randomly selected 28 birds per treatment (four birds per pen) through brachial venipuncture into plain tubes, centrifuged

(2800× g, at 7 °C, for 10 min), and the resultant serum was analyzed for lipids.^[31]

2.3. Carcass Traits

On day 21, 35 birds that were randomly selected from each treatment (five birds per pen), were weighed and euthanized, and the carcasses were defeathered and eviscerated. The weight of carcass, retail cuts, and fat depots^[32,33] (abdominal, mesentery, neck, and sartorial fats) were recorded and carcass yield was calculated.

2.4. Caeca pH and Bacterial Counts

Caeca digesta was collected from four birds per replicate for pH determination and the culturing and counting of *Escherichia coli*, *Lactobacilli* spp., and *Salmonella* spp. according to standard procedures.^[34–36] Cecal digesta pH was immediately measured after slaughter with a precalibrated digital pH meter (MW102 pH meter, Milwaukee Instruments, Inc., Rocky Mount, NC). For culturing, 1 g of digesta was put in a test tube that contains 9 mL of sterile peptone water. The mixture was vortexed and dilution was made up to 10^{−10}. Afterward, 1 mL of the 10^{−10} dilution was put into petri dishes, and a sterile molten agar was added. *E. coli* was cultured on eosin methylene blue agar (Merck-1.01347.0500, Merck KGaA, Darmstadt, Germany) and incubated for 24 h at 37 °C. *Salmonella* spp. was counted on *Salmonella Shigella* agar (Merck-107667, Merck KGaA, Darmstadt, Germany) and incubated for 48 h at 37 °C. *Lactobacilli* spp. was cultured on Man Rogosa Sharpe agar (Merck-1.10660.500, Merck KGaA, Darmstadt, Germany) and incubated for 48 h at 37 °C.

2.5. Fatty Acids Analysis

The total lipids in diets and breast meat were extracted according to the procedure of Folch et al.^[37] using chloroform:methanol (2:1 v/v). Extracted lipids were transesterified to obtain the fatty acid methyl esters (FAME) by treating with 14% methanolic BF₃ and 0.66 N methanolic KOH following the AOAC^[30] methods. Gas chromatograph mass spectrometer (GCMS QP2010SE, Shimadzu, Japan) was used to separate FAME as described earlier.^[38]

2.6. Meat Quality

Breast meat pH was measured in distil H₂O homogenate (1:4 m/v) with a precalibrated digital pH meter (MW102 pH meter, Milwaukee Instruments, Inc., Rocky Mount, NC). Cooking and drip losses, and color coordinates were measured as described earlier.^[39] Malondialdehyde and protein carbonyl contents were determined with ELISA kits (MyBiosource, San Diego, CA) in line with the protocol of the manufacturers.

2.7. Statistical Analysis

This trial followed a 2 (Oil type) × 2 (feed restriction) factorial outlay in a completely randomized design model. Data were checked

for homogeneity of variance and normality prior to analysis. Data were analyzed with SAS software using the following model

$$Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \delta_{ij},$$

where

Y_{ij} = observed dependent variable;

μ = overall mean;

α_i = effect of dietary oil type (OT);

β_j = effect of late feed restriction (FR);

$(\alpha\beta)_{ij}$ = interaction between OT and FR; and

δ_{ij} = random error.

When the *F*-test is significant ($P < 0.05$), least square means were separated with the PDIFF option of SAS.

3. Results and Discussion

3.1. Growth Performance and Serum Indices

The growth indices in female broilers as influenced by dietary OT and late FR are presented in **Table 2**. Independent of OT, unrestricted birds presented heavier ($P < 0.05$) BW and BWG than the feed-restricted birds. This observation was anticipated because the unrestricted birds consumed more feed, which allowed them to meet and probably exceed their basal nutrient requirements. Consistently, feed-restricted broilers presented lighter BWG than their unrestricted counterparts.^[12,40–43] However, no significant changes in BWG were observed in birds subjected to 10%,^[44] 20%,^[44,45] and 35%^[45] FR. In spite of the heavier BW and BWG in the unrestricted birds compared with their restricted counterparts, it is noteworthy that the BW and BWG of the SR birds were not significantly different from those of the PN birds. This observation infers that the severity of the reductions in BW and BWG associated with the 25% FR was somewhat lesser in the SO birds compared with the PO birds.

The SO birds presented better FCR than the PO birds. A possible reason for this finding could be that SO is rich in polyunsaturated fatty acids (PUFA), which are highly digestible and readily absorbed and thus enhanced available metabolizable energy compared with saturated fatty acids (SFA) that are abundant in PO.^[46–49] In agreement with the current findings, broilers supplemented with diets abundant in PUFA presented heavier BW and better FCR than those supplemented with diets abundant in SFA^[20,23,25] suggesting that fatty acid (FA) digestibility increases as the degree of unsaturation increases.^[49,50] Albeit the SN and SR birds had similar FCR, the PR birds presented better FCR than the PN birds. This infers that the high digestibility of PUFA present in the SO remarkably masked the poor FCR that is often associated with ad libitum feeding in broilers. This poor FCR manifested in the PN birds due to the poor digestibility and absorption of SFA present in the PO, but this effect was partly alleviated with the 25% FR culminating in a better FCR in the PR birds.

The OT–FR interaction was not significant ($P > 0.05$) for serum lipids in female broilers (**Table 3**). Dietary OT did not significantly influence ($P > 0.05$) serum lipids in broilers. This response was unanticipated because one would expect a higher concentration of serum lipids in the PO birds since the PO-based diet contained more SFA (37%) and lesser PUFA (23.7%) than

Table 2. Effect of dietary oil type and late quantitative feed restriction on growth performance of female broiler chickens.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item								
Initial Body weight (g per bird)	803	802	803	803	15.78	0.958	0.958	0.958
Final body weight (g per bird)	2225 ^b	1950 ^c	2500 ^a	2142 ^b	73.92	0.005	0.0004	0.579
Weight gain (g per bird)	1422 ^b	1148 ^c	1698 ^a	1338 ^b	71.84	0.004	0.0003	0.561
Average daily weight gain (g per bird d ^{−1})	67.7 ^b	54.7 ^c	80.8 ^a	63.7 ^b	3.42	0.004	0.0003	0.561
Feed intake (g per bird)	2997 ^a	2267 ^b	3010 ^a	2270 ^b	50.06	0.115	<0.0001	0.334
Average daily feed intake (g per bird d ^{−1})	143 ^a	108 ^b	143 ^a	108 ^b	5.56	0.113	<0.0001	0.333
Feed conversion ratio	2.14 ^a	1.99 ^b	1.81 ^c	1.71 ^c	0.09	0.004	0.199	0.019

^{a,b,c}Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (eight birds per replicate) per treatment group. SEM = standard error of mean.

Table 3. Serum biochemical parameters in female broiler chickens as influenced by dietary oil type and late quantitative feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item [mg dL ^{−1}]								
Total cholesterol	289 ^a	207 ^b	278 ^a	215 ^b	27.61	0.943	0.018	0.733
Triglycerides	320 ^a	264 ^b	302 ^a	241 ^b	26.60	0.456	0.044	0.920
HDL-C	129 ^a	92.1 ^b	124 ^a	95.5 ^b	12.20	0.943	0.018	0.733
LDL-C	96.7 ^a	62.2 ^b	93.7 ^a	70.9 ^b	13.29	0.831	0.047	0.665
VLDL-C	63.9 ^a	52.8 ^b	60.5 ^a	48.2 ^b	5.33	0.465	0.044	0.920

^{a,b}Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (four birds per replicate) per treatment group. HDL-C-high density lipoprotein cholesterol, LDL-C-low density lipoprotein cholesterol, VLDL-very low-density lipoprotein. SEM = standard error of mean.

the SO-based diet which contained lesser SFA (16%) and more PUFA (59%). It has been established that PUFA-rich diets can suppress chylomicron secretion from intestinal cells, and hepatic fatty acid synthesis characterized by the conversion of acetyl-CoA to glycerides,^[51,52] and consequently lower serum cholesterol and triglycerides in broilers.^[23,25] However, the biological activities and absorption of dietary FA depend on their positional distribution.^[53,54] In this study, C16:0 was the major SFA in the diets accounting for about 32.4% and 11.6% of the total fatty acids in the PO- and SO-based diets, respectively. Compared to other sources of SFA such as lard, whose C16:0 is largely found on the sn-2 position of the dietary triacylglycerol, the C16:0 in PO is positioned at the sn-1 and sn-3,^[55–57] which reduces its digestibility, and consequently reducing its cholesterol raising capacity.^[57–59] Moreover, in this study, we utilized red palm oil, which is rich in tocopherol and tocotrienols that are capable of reducing cholesterol synthesis by post-transcriptional reduction in the activity of hydroxy methyl glutaryl-coenzyme A reductase, the rate limiting step in endogenous cholesterol synthesis.^[60–62] If this was the case, the cholesterol raising effect of the C16:0 in the PO diet would, at least, be partly counteracted. This could probably account for the lack of statistically significant differences in serum lipids between the OTs. Similar to the current findings, Benzertiha et al.^[63] found no significant differences in serum total cholesterol in broilers supplemented with PO, poultry fat or insect (*Tenebrio molitor*) oil in spite of the lower SFA

in the poultry fat and insect oil-based diet compared to that of PO-based diet. Contrarily, PO-supplementation increased serum cholesterol, and triglycerides in broilers.^[23,25] We speculate that the discrepancies in the response of serum lipids in broilers to dietary PO may be due to the variation in the types and levels of PO utilized in addition to myriad experimental conditions such as the age, breed and sex of birds, and rearing conditions.

Feed-restricted birds had lesser ($P < 0.05$) total cholesterol, triglycerides, LDL-C, HDL-C, and VLDL-C than the unrestricted birds (Table 3). Reduced serum cholesterol may indicate decreased fat metabolism as a consequence of reduced fat intake in the SR and PR birds. Moreover, the reduced triglycerides in the feed-restricted birds may imply that the SR and PR birds utilized most of the triglycerides to meet their energy demand during FR.^[3,64,65] Correspondingly, broilers subjected to 8 h d^{−1} FR from 21 to 35 d had lowered serum cholesterol compared with ad libitum fed birds.^[40] Moreover, a 25% FR for one or two weeks lowered total cholesterol, triglycerides, LDL-C, and VLDL-C in broiler chickens.^[66]

3.2. Caecal pH and Bacterial Counts

The caeca pH and selected bacterial populations in female broilers supplemented with different OTs and subjected to 25% FR are outlined in Table 4. The interaction between dietary OT and FR

Table 4. Caeca bacterial counts in female broiler chickens supplemented with different oil types and subjected to late quantitative feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item								
pH	6.18 ^b	5.90 ^c	6.76 ^a	6.20 ^b	0.06	<.0001	<0.0001	0.042
Microbe (log ₁₀ CFU g ⁻¹)								
<i>Lactobacillus</i> spp.	5.24 ^b	5.82 ^a	5.08 ^b	5.70 ^a	0.13	0.286	0.000	0.877
<i>E. coli</i>	3.43 ^a	3.04 ^b	3.60 ^a	3.35 ^a	0.11	0.024	0.004	0.483
<i>Salmonella</i> spp.	3.60 ^a	2.94 ^b	3.62 ^a	3.00 ^b	0.11	0.731	<0.0001	0.853

^{a,b}Means in a row with no common superscript differ significantly ($P < 0.05$). CFU, colony forming unit. SEM = standard error of mean. Values are mean of seven replicates (four birds per replicate) per treatment group.

was significant ($P < 0.05$) for caeca pH. The highest ($P < 0.05$) and lowest ($P < 0.05$) caecal pH was recorded in the SN and PR birds, respectively. Caecal pH in the PN and SR birds was similar ($P > 0.05$). Caecal pH may be the cause or result of different fermentation types in the caecum.^[67] Unrestricted feeding may encourage the fermentation of undigested protein in the caeca, and the fermentation products such as biogenic amines, H₂S, NH₃, NO, branched chain fatty acids, indoles and phenols, could increase caecal pH.^[67,68] Thus, FR would lower caecal pH due to the reduction in the fermentation of undigested protein and its fermentation products. This may explain the low caecal pH in the PR birds compared with the PN birds, and in the SR birds compared with the SN birds. Moreover, medium chain fatty acids (MCFA) can reduce gut pH by reducing acid production from bacteria.^[69,70] The PO diet contained 0.33% C12:0 while the SO diet had 0.04% C12:0 (Table 1). This may explain the low caecal pH in the PO birds compared with the SO birds. Likewise, birds supplemented with palm kernel fatty acid distillers had lower caeca pH than those supplemented with SO and beef tallow.^[71] The PN and SR birds had similar caecal pH, which was lower than that of the SN birds and higher than that of the PR birds. This finding suggests that dietary MCFA and reduced fermentation of undigested protein in the caeca can independently lower caecal pH. Thus, the combination of these factors would exert a synergistic effect as reflected in the lower caeca pH of the PR birds.

Caeca *Lactobacillus* and *Salmonella* counts did not differ with oil types. Feed-restricted birds had more ($P < 0.05$) *Lactobacillus* spp. count and lesser ($P < 0.05$) *Salmonella* spp. count than the unrestricted birds. The lower pH in the feed-restricted birds might have encouraged the proliferation of *Lactobacillus* spp., which explains their relative abundance in the caeca. This consequently led to the decline in the *Salmonella* spp. and *E. coli* counts in the caeca of the feed-restricted birds. This finding is partly consistent with those of Jahanpour et al.^[72] in which a 25% FR for 14 d improved *Lactobacillus* and *Enterobacteriaceae* counts in broilers. The PR birds presented lower ($P < 0.05$) *E. coli* counts than the birds in other treatments. The finding may partly reflect the reduction in pH and the antimicrobial effect of MCFA, especially C12:0. Generally, fatty acids exert antimicrobial effect, and their potency depends on the chain length and degree of saturation of FA, and the environmental pH.^[70] Gantois et al.^[73] reported that MCFA supplementation reduced *Salmonella* spp. and *E. coli* counts in broilers.

3.3. Carcass Traits and Fat Depots

The SN and PR birds presented the heaviest ($P < 0.05$) and lightest ($P < 0.05$) carcass weight, respectively (Table 5). The PN and SR birds had similar carcass weight that was lighter ($P < 0.05$) than those of the SN birds and heavier ($P < 0.05$) than those of the PR birds. The trend of these results was anticipated, and it aligns with the results of the BW of the birds. Unhindered access to feed would improve carcass weight due to the availability of ample nutrients required for muscle and fat accretion. Similarly, a reduction in carcass weight was observed in birds fed for 8 h d⁻¹ from 21 to 35 d.^[40] However, broilers subjected to FR for 6 h d⁻¹ from fourth to fifth week^[74] and fed for 8 h d⁻¹ from 7 to 21 d and 14 to 28 d^[40] had similar carcass weight as those fed ad libitum. The severity and duration of FR may account for the discrepancies in results between studies.

The PN and SR birds had similar carcass weight in spite of the differences in their access to feed. This finding might indicate the high digestibility, and better intestinal absorption of PUFA that were abundant in SO compared to the abundant SFA in the PO. The PN and SR birds had the least and highest carcass yield ($P < 0.05$), respectively. Carcass yield in the PR and SN birds was similar. The low carcass yield in the PN birds appears to be a consequence of intensive fat deposition, especially in the separable fat depots, which were trimmed off during processing. Nonetheless, the application of 25% FR ameliorated the low carcass yield as reflected in the PR birds. The similarity in carcass yield between the PR and SN birds and the higher carcass yield in the SR birds infer a synergy between FR and OT on carcass yield in female broilers. Neither OT nor FR influenced ($P > 0.05$) retail carcass cuts in broiler chickens. Consistently, dietary OT did not affect carcass cuts in broilers.^[20,75] Furthermore, a 10% and 20% FR did not affect carcass cuts in broiler chickens.^[76]

The interaction between OT and FR for the weight of fat in different fat depots in female broilers was significant ($P < 0.05$) (Table 6). The PN birds deposited more ($P < 0.05$) fat in the abdomen, mesentery, neck, and sartorial region, and thus had more ($P < 0.05$) total separable fat depot (SFD) and total fat depot compared with birds in other treatments. The SR birds deposited lesser ($P < 0.05$) abdominal fat, mesentery fat, and neck fat than the SN birds. However, sartorial fat was not different between the SN and SR birds. Lesser abdominal, mesentery, neck, and sartorial fats were deposited in the PR birds compared with the PN

Table 5. Carcass traits in female broilers supplemented with different oil types and subjected to late quantitative feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item								
Slaughter weight (SW, g per bird)	2130 ^b	1910 ^b	2460 ^a	2010 ^b	76.9	0.013	0.001	0.155
Carcass weight (CW, g per bird)	1410 ^b	1280 ^c	1720 ^a	1490 ^b	81.8	0.006	0.044	0.549
Carcass yield (%)	66.1 ^c	70.6 ^b	69.8 ^b	73.9 ^a	1.07	0.063	0.026	0.945
Retail cuts (g kg ⁻¹ CW)								
Wing	96.3	104	103	98.1	3.02	0.881	0.669	0.062
Drumstick	129	120	121	121	5.41	0.892	0.968	0.903
Thigh	132	135	137	132	6.78	0.906	0.936	0.529
Breast	336	330	318	331	8.94	0.363	0.719	0.309
Back	317	311	322	319	9.63	0.518	0.665	0.864

^{a,b,c}Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (five birds per replicate) per treatment group. SEM = standard error of mean.

Table 6. Fat depots in female broiler chickens supplemented with different oil types and subjected to late quantitative feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item (g kg ⁻¹ live weight)								
Abdominal fat	20.60 ^a	11.30 ^{bc}	13.00 ^b	9.70 ^c	1.01	0.000	<0.0001	0.008
Mesentery fat	6.17 ^a	2.26 ^c	3.60 ^b	2.43 ^c	0.35	0.004	<0.0001	0.002
Neck fat	5.14 ^a	1.84 ^c	3.13 ^b	2.10 ^c	0.29	0.008	<0.0001	0.001
Sartorial fat	2.68 ^a	1.09 ^b	1.56 ^b	1.21 ^b	0.16	0.009	<0.0001	0.002
Total separable fat depot	13.90 ^a	5.18 ^c	8.30 ^b	5.74 ^c	0.80	0.006	<0.0001	0.001
Total fat depot	34.60 ^a	15.50 ^c	21.30 ^b	16.30 ^c	1.69	0.001	<0.0001	0.002

^{a,b,c}Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (five birds per replicate) per treatment group. SEM = standard error of mean.

birds. Fat accretion in the abdomen, mesentery, neck, and sartorial regions, as well as total SFD and total fat depot were not different between the PR and SR birds. Fatty acids that are available for accretion in birds are predominantly from absorption, de novo synthesis and β -oxidation of FA.^[53,77,78] The lower fat accretion in different fat depots in the SO birds may be related to the high PUFA content of SO, which inhibits de novo lipid synthesis in the liver, and has high proclivity to oxidize.^[48,53,77,78] Moreover, PUFA can improve diet-induced thermogenesis.^[79,80] Furthermore, PUFA are preferentially accreted as membrane phospholipids, in a different manner from SFA, which if consumed in excess are accreted as triglycerides in fatty tissues.^[81] Consistent with our results, dietary supplementation of PUFA-rich oils in broilers lowered abdominal fat^[23,25,48,80] and separable fat depots^[26] compared to the SFA-rich oils.

The reduced fat accretion in different fat depots in the restricted birds may be due to reduced fat intake, which lowers the activity of hepatic acetyl-CoA carboxylase-5 activity, a rate-limiting enzyme for fatty acid synthesis.^[77,78] This could limit hepatic triglyceride synthesis and consequently, a reduction in body fat accretion.^[77,78] Moreover, the feed-restricted birds might have mobilized the body fats to meet the prevailing energy de-

mand during restriction.^[81,82] The current findings concur with those of Omosebi et al.^[41] and Boostani et al.^[40] who reported a lower abdominal fat in FR birds. Contrarily, Demir et al.^[3] did not observe changes in abdominal fat following FR in birds while FR for 6 h d⁻¹ from third to fourth week and from fourth to fifth week improved abdominal fat in broilers.^[66] The potency of the 25% FR to lower fat accretion in the total fat depots was higher in the PO (55%) birds than the SO (24%) birds due to the higher fat accretion potential of PO compared with SO.

3.4. Muscle Fatty Acids

The FA profile in breast meat of female broilers is presented in **Table 7**. The intramuscular fat and total FA reflected the trend in other fat depots. The alteration in individual FA appears to be due to the alterations in the total FA induced by OT, FR, and/or their interactions. The prominent FA in the PO and SO birds was C18:1n-9 and C18:2n-2, respectively. This result agrees with the finding of previous studies.^[23,25] Independent of FR, the SO meats presented lesser ($P < 0.05$) C12:0, C14:0, C14:1n-7, C16:0, C16:1n-7; C18:1n-9, and C18:0 and more ($P < 0.05$) C18:2n-6 and

Table 7. Fatty acid composition of breast meat in female broilers supplemented with different oil types and subjected to late feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item (mg per 100 g fresh meat)								
C12:0	6.83 ^a	4.53 ^b	4.02 ^c	3.24 ^d	0.65	<0.0001	<0.0001	<0.0001
C14:0	30.56 ^a	25.97 ^b	14.18 ^c	7.17 ^d	1.09	<0.0001	<0.0001	<0.0001
C14:1n-7	33.43 ^a	30.80 ^b	14.05 ^c	15.10 ^c	1.67	<0.0001	<0.0001	<0.0001
C16:0	934.50 ^a	791.24 ^b	700.91 ^c	631.35 ^d	14.21	<0.0001	<0.0001	<0.0001
C16:1n-7	24.50 ^a	24.20 ^a	17.08 ^b	17.98 ^b	1.45	<0.0001	0.131	0.002
C18:0	445.50 ^a	290.28 ^c	344.61 ^b	296.16 ^c	15.66	<0.0001	<0.0001	<0.0001
C18:1n-9	1238.00 ^a	1025.00 ^b	548.10 ^c	494.10 ^d	23.45	<0.0001	<0.0001	<0.0001
C18:2n-6	523.50 ^c	560.72 ^b	1191.87 ^a	1183.40 ^a	10.00	<0.0001	<0.0001	<0.0001
C18:3n-3	29.40 ^c	47.11 ^b	118.50 ^a	117.50 ^a	4.21	<0.0001	<0.0001	<0.0001
C20:4n-6	160.30 ^a	142.00 ^b	145.35 ^b	163.40 ^a	10.10	0.015	1.000	<0.0001
C20:5n-3	25.90 ^b	25.97 ^b	37.60 ^a	38.00 ^a	3.11	<0.0001	0.748	0.345
C22:5n-3	24.16 ^d	32.38 ^c	48.20 ^b	54.00 ^a	3.33	<0.0001	<0.0001	0.006
C22:6n-3	22.00 ^c	20.60 ^c	42.60 ^b	47.20 ^a	2.10	<0.0001	00.005	<0.0001
ΣSFA	1416.89 ^a	1111.31 ^b	1063.41 ^c	937.95 ^d	13.98	<0.0001	<0.0001	<0.0001
ΣMUFA	1296.11 ^a	1079.76 ^b	579.57 ^c	527.47 ^d	16.00	<0.0001	<0.0001	<0.0001
ΣPUFA	784.00 ^d	829.36 ^c	1583.40 ^b	1600.80 ^a	14.12	<0.0001	<0.0001	<0.0001
Σn-6	683.40 ^b	708.20 ^c	1337.22 ^b	1346.10 ^a	7.22	<0.0001	<0.0001	<0.0001
Σn-3	100.60 ^d	126.60 ^c	246.45 ^b	254.81 ^a	8.21	<0.0001	<0.0001	<0.0001
n-6/n-3	6.79 ^a	5.55 ^b	5.43 ^{bc}	5.28 ^c	0.32	<0.0001	<0.0001	<0.0001
PUFA/SFA	0.55 ^d	0.75 ^c	1.49 ^b	1.71 ^a	0.05	<0.0001	<0.0001	0.002
Total fatty acid	3497 ^a	3020 ^d	3226 ^b	3066 ^c	23.95	<0.0001	<0.0001	<0.0001

^{a,b,c,d} Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (five birds per replicate) per treatment group. SEM = standard error of mean. SFA, saturated fatty acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid. ΣSFA = (C12:0 + C14:0 + C16:0 + C18:0), ΣMUFA = (C16:1n-7 + C16:1n-9 + C18:1n-9), Σn-3 = (C18:3n-3 + C20:5n-3 + C22:5n-3 + C22:6n-3), Σn-6 = (C18:2n-6 + C20:4n-6), ΣPUFA = (Σn-3 + Σn-6).

C18:3n-3 than the PO meats. These findings reflect dietary FA. Moreover, SO is abundant in PUFA, which reduces de novo FA synthesis and improves β -oxidation.^[26,48,80] The higher contents of C20:5n-3, C22:5n-3, and C22:6n-3 in the SO meats were concordant with the higher C18:3n-3 contents because these FA are long-chain metabolites of C18:3n-3. Similar findings have been reported by previous workers.^[23,25,26,48,80] Breast meat of the unrestricted birds presented more ($P < 0.05$) SFA and monounsaturated fatty acids (MUFA) and lesser ($P < 0.05$) PUFA than the meat of the restricted birds. This observation can be ascribed to the increased total FA in the meat of the unrestricted birds. Increased muscle fatness is largely accompanied with an increase in the accretion of neutral lipids, in which SFA and MUFA are preferentially deposited compared with PUFA.^[81–83] This may explain why the meat of the PN and SN birds had more C18:0 and C18:1n-9, suggesting an increase in the activity of stearoyl Co-A desaturase enzyme, which converts C18:0 to C18:1n-9. In addition, the deposition of PUFA in the restricted birds might have repressed the enzymes responsible for de novo synthesis of C18:1n-9 from C18:0.^[26,48,80] A spectacular observation in this study was that the OT–FR interaction was significant ($P < 0.05$) for all FAs except C20:5n-3. Moreover, some FA were differentially deposited among the treatments. While the SN and SR meats had similar C18:3n-3 and C18:2n-6, the PR had more ($P < 0.05$) C18:3n-3 and C18:2n-6 than the PN meat. The relative

abundance of specific FA in each oil and their proclivity to be deposited in muscle neutral lipids and phospholipids might have played a role. This observation further affirms our hypothesis that FA metabolism in FR birds was dependent on dietary OT.

3.5. Chemical Composition and Quality of Breast Meat

Neither OT nor FR influenced the ash and protein content of breast meat in female broilers (Table 8). The PN meat had lesser ($P < 0.05$) moisture content than other meats. Moisture content in the PR, SN, and SR meat did not differ. The PN meat had the highest ($P < 0.05$) ether extract among the meats. Ether extract in the SR meat did not differ from those of PR and SN meat. The PR meat had lower ($P < 0.05$) ether extract than the PN and SN meats. The lower moisture content in the PN meat may be attributed to its high ether extract content, which was caused by the unrestricted access to feed and high proclivity of PO to induced fat accretion. Thus, restricted access to the PO diets would reduce the accretion of intramuscular fat as reflected in the PR meat. A similar scenario was expected in the SO birds but the fat content of the SN and SR meat did not differ, indicating the low proclivity of SO to induce fat accretion in broilers. The reduction in ether extract of the PR meat was consistent with the findings of Omosebi et al.^[41] who observed that a 40% FR reduced the

Table 8. Chemical composition of breast meat in female broiler chickens supplemented with different oil types and subjected to late quantitative feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item [g kg ^{−1}]								
Moisture	721 ^b	729 ^a	726 ^a	727 ^a	1.66	0.521	0.701	0.003
Protein	227	226	226	227	1.64	0.829	0.467	0.135
Ether extract	36.0 ^a	29.4 ^c	32.2 ^b	31.0 ^{bc}	0.48	0.032	<0.0001	<0.0001
Ash	15.5	15.6	15.6	15.4	0.33	0.984	0.883	0.746

^{a,b}Means in a row with no common superscript differ significantly ($P < 0.05$). Values are mean of seven replicates (five birds per replicate) per treatment group. SEM = standard error of mean.

Table 9. Breast meat quality in female broiler chickens supplemented with different oil types and subjected to late feed restriction.

Oil type (OT)	Palm oil		Soybean oil		SEM	OT	P-value	
	–	+	–	+			FR	OT × FR
25% Feed restriction (FR)								
Item								
pH	5.72	5.71	5.71	5.72	0.62	0.898	1.000	0.797
Drip loss (%)	2.81	2.64	2.79	2.84	0.22	0.147	0.765	0.219
Cook loss (%)	22.5	26.4	24.7	25.9	3.34	0.363	0.088	0.241
Lightness	45.5	45.4	45.8	45.8	5.21	0.463	0.917	0.871
Redness	3.65	3.63	3.58	3.53	0.45	0.454	0.746	0.914
Yellowness	8.08	8.37	8.18	8.25	0.75	0.972	0.560	0.727
Malondialdehyde (mg MDA kg ^{−1})	0.12	0.11	0.12	0.12	0.04	0.099	0.110	0.101
Carbonyl (μmol mg ^{−1} protein)	0.23	0.22	0.22	0.22	0.06	0.168	0.328	0.189

Note: Values are mean of seven replicates (five birds per replicate) per treatment group. SEM = standard error of mean.

fat content of breast meat while a 20% FR did not affect the fat content of breast meat. Moreover, a 30% FR in female and male broiler chickens for 14–21 d enhanced moisture content and lowered ether extract of breast meat.^[84]

Neither OT nor FR affected the quality of breast meat in female broilers (Table 9). The similar pH may indicate that muscle glycogen content, the primary driver of postmortem muscle metabolism was not affected^[85] despite the 25%-FR employed in this study. Water holding capacity and color of meat are largely dependent on muscle pH.^[86] Thus, the similarity in color coordinates and drip and cook losses were envisaged because of the similarity in the muscle pH. Similar to the current findings, a 30% FR from day 14 to 21 did not affect the muscle pH, color and water holding capacity of breast meat in male and female broilers.^[84] No difference ($P > 0.05$) in the malondialdehyde and carbonyl contents was found among the treatment groups, suggesting that the antioxidant/oxidative status of breast meat was unaffected.

4. Conclusion

The current results revealed that 25% FR lowered body and carcass weights in female broilers, but the severity of the reduction was more in the PO birds than in the SO birds. Albeit the SO birds had better feed efficiency than the PO birds, the ap-

plication of 25% FR improved feed efficiency in the PO birds. The 25% FR improved carcass yield in the PO and SO birds. Feed-restricted birds had lower serum lipids and caeca *Salmonella* spp. and more *Lactobacillus* spp. counts than the unrestricted birds. Feed-restricted PO birds had the lowest caecal pH and *E. coli* counts. The weights of fat depots were affected by the OT–FR interactions. The OT–FR interaction was significant for all fatty acids except C20:5n-3. The SN and SR meats had similar C18:3n-3 and C18:2n-6, while the PR meat had more C18:3n-3 and C18:2n-6 than the PN meat. It could be surmised that the impact of 25% FR on growth performance, carcass yield, caecal pH and selected bacteria, and fat accretion in separable fat depots and muscle lipids in female broilers depend on the oil type. Thus, dietary oil type should be taken into cognizance when applying quantitative FR strategies in broiler production.

Conflict of Interest

The authors declare no conflict of interests.

Author Contributions

K.A.: conceptualized, designed, and conducted the experiment, analyzed and interpreted the data, wrote and revised the manuscript. F.S.-O., O.A., O.A., and A.El-I.: contributed materials and reagents, and performed the

experiment. A.A., S.A., O.O., and F.O.: conducted the experiment and collected the data. All authors read and approved the paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

broiler chickens, feed restrictions, meat quality, oil types, serum lipids

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