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Growth performance and fatty acid composition of mealworm (*Tenebrio molitor* L.) fed *Washingtonia Filifera* (Lindl.) H.Wendl. fruit powder

[*Desempenho de crescimento e composição de ácidos graxos de larvas de tenébrio (*Tenebrio molitor *L.) alimentadas com pó do fruto de* Washingtonia filifera *(Lindl.) H.Wendl.*]

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ABSTRACT

The use of agricultural byproducts as alternative feed ingredients is increasing due to their low cost and sustainability. Fruits of *Washingtonia filifera* (OPF) represent an underutilized resource with potential to partially replace wheat bran (WB) in *Tenebrio molitor* diets. This study assessed the effects of different OPF–WB ratios on larval survival, growth, and development. Larvae were reared for six weeks on diets containing 0–100% OPF. Survival and body weight were measured at weeks two, four, and six. Pupal and adult weights were also recorded. The chemical composition of n-hexane extracts was analyzed using GC–MS. Survival remained high during the first two weeks (96.4–98.8%). By week four, survival significantly decreased in the OPF-only group (81.25 ± 2.43%) compared with mixed diets and the WB control (95.50–97.50%). After six weeks, OPF-only larvae had the lowest survival (73.00 ± 1.73%), while mixed diets maintained 89.00–96.50%. Larval, pupal, and adult weights were also reduced under the OPF-only diet, whereas diets containing 25–75% OPF supported growth similar to WB. GC–MS revealed comparable fatty acid profiles dominated by linoleic and palmitic acids. Overall, moderate OPF inclusion can support sustainable *T. molitor* production.

Keywords: insect farming, alternative feed resources, larval development, GC–MS profiling, linoleic acid

RESUMO

O uso de subprodutos agrícolas como ingredientes alternativos para ração animal está aumentando devido ao seu baixo custo e sustentabilidade. Os frutos de Washingtonia filifera *(OPF) representam um recurso subutilizado com potencial para substituir parcialmente o farelo de trigo (FT) em dietas para* Tenebrio molitor. *Este estudo avaliou os efeitos de diferentes proporções de OPF e FT na sobrevivência, no crescimento e no desenvolvimento larval. As larvas foram criadas por seis semanas em dietas contendo de 0 a 100% de OPF. A sobrevivência e o peso corporal foram medidos nas semanas dois, quatro e seis. Os pesos das pupas e dos adultos também foram registrados. A composição química dos extratos de n-hexano foi analisada por GC-MS. A sobrevivência permaneceu alta durante as duas primeiras semanas (96,4–98,8%). Na quarta semana, a sobrevivência diminuiu significativamente no grupo alimentado apenas com OPF (81,25±2,43%) em comparação às dietas mistas e ao grupo controle com FT (95,50–97,50%). Após seis semanas, as larvas alimentadas exclusivamente com OPF apresentaram a menor taxa de sobrevivência (73,00±1,73%), enquanto as dietas mistas mantiveram taxas de 89,00–96,50%. Os pesos das larvas, das pupas e dos adultos também foram reduzidos na dieta com OPF, enquanto as dietas contendo 25–75% de OPF promoveram crescimento semelhante ao da dieta WB. A análise por GC-MS revelou perfis de ácidos graxos comparáveis, com predominância de ácidos linoleico e palmítico. Em geral, a inclusão moderada de OPF pode viabilizar a produção sustentável de* T. molitor.

Palavras-chave: criação de insetos, fontes alternativas de alimentação, desenvolvimento larval, perfil GC-MS, ácido linoleico

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INTRODUCTION

The rapid expansion of insect farming has intensified the search for novel and sustainable feed ingredients capable of enhancing insect growth performance and nutritional value (Van Huis and Oonincx, 2017, Gautam *et al.*, 2025). Commonly farmed insects include *Tenebrio molitor, Hermetia illucens, Acheta domesticus*, and *Alphitobius diaperinus*. Among these, T. molitor (yellow mealworm) has emerged as one of the most promising species for large-scale production due to its efficient feed conversion, relatively low environmental footprint, and high content of quality protein and lipids (Grau *et al.*, 2017; Bordiean *et al.*, 2020; Jankauskienė *et al.*, 2024; Abutaha and Al-Mekhlafi, 2025; Huang *et al.*, 2025). Optimizing its nutrient profile particularly its fatty acid composition remains a central goal for improving its suitability as an ingredient for livestock feed food applications (Mattioli *et al.*, 2024; Siddiqui *et al.*, 2024,). Recent studies emphasize that manipulating larval diets with plant-derived additives can substantially modify growth kinetics, survival, and biochemical composition, thereby enhancing the functional quality of mealworm biomass (Liu *et al.*, 2020; Montalbán *et al.*, 2022, 2023; Lisboa *et al.*, 2025). Nonetheless, systematic research on regionally available, underutilized botanicals as dietary supplements for *T. molitor* remains limited.

Washingtonia filifera, commonly known as the California fan palm, produces nutrient-rich fruits traditionally consumed in various indigenous diets. These fruits contain a diverse array of bioactive compounds, including unsaturated fatty acids, phenolics, antioxidants, and micronutrients that could support insect metabolic processes and modulate lipid biosynthesis (El-Sayed *et al.*, 2006; Hammami *et al.*, 2011, Nehdi, 2011, Abutaha *et al.*, 2023). Although the phytochemical properties of *W. filifera* have been documented, its potential role as a functional feed additive in insect rearing systems has not been explored. Leveraging such underused plant resources aligns with the global drive toward circular bioeconomy strategies and sustainable feed sourcing, particularly in arid regions where *W. filifera* naturally thrives.

In recent years, growing interest has focused on converting agricultural and food-processing residues into cost-effective substrates for insect farming, including the rearing of yellow mealworm larvae (Van Huis and Oonincx, 2017, Stull *et al.*, 2019, Brai *et al.*, 2023). Mealworms are omnivorous and capable of degrading cellulose (Przemieniecki *et al.*, 2020; Rho and Lee, 2022) which makes them suitable candidates for utilizing fibrous waste streams. This ability suggests that large-scale production of mealworms could be achieved with reduced feed costs while simultaneously adding value to agricultural byproducts. However, although their capacity to bioconvert low-quality organic materials is documented (Ruschioni *et al.*, 2020), information on the digestibility and nutritional suitability of many by-products for mealworms remains limited. To address this gap, the present study investigated how diets formulated with *W. filifera* fruit powder, included at varying levels, affect the growth performance and fatty acid composition of mealworm. Therefore, this study evaluates the potential of *W. filifera* fruit powder as a natural dietary additive for *T. molitor* larvae. Specifically, we assess its impact on growth performance parameters and determine its influence on the fatty acid composition of mealworm larvae. By addressing these knowledge gaps, the present work provides novel insights into the use of desert-adapted plant resources to enhance insect farming outputs and supports the development of sustainable, nutritionally optimized insect-based feed ingredients.

ETHICAL ASPECTS

This research was not submitted to the *Ethics Committee on Animal Use*.

MATERIALS AND METHODS

Yellow mealworm larvae were maintained in the insect-rearing facility at King Saud University (Riyadh, Saudi Arabia) under controlled conditions of $23 \pm 2°C$, $40 \pm 5\%$ relative humidity, and a 12-hour light/dark cycle. The larvae were housed in plastic crates ($60 \times 40 \times 14$cm) and fed a diet consisting of wheat bran as dry feed and fresh cabbage as wet feed. Cabbage was sourced locally in Riyadh and kept refrigerated at 4°C until it was used.

Control groups were provided with wheat bran alone, while experimental groups received wheat

bran mixed with *W. filifera* fruit (OPF) powder at ratios of 100%, 75%, 50%, and 25% (w/w). OPF fruit were dried in an oven at 60°C for 72 hours and stored at -80°C until use. Feeding trials were conducted in plastic trays ($7 \times 7 \times 7$cm), each containing 30g of feed for 50 larvae, with four replicates per treatment. Larvae were kept in an incubator (Sanyo, Japan) set at 25°C and 50 ± 5% relative humidity. Larval weights were recorded at weeks 2, 4, and 6 using an analytical balance, and average individual weight per tray was calculated. After six weeks, the larvae were harvested for further analysis. Prior to harvesting, they were starved for 24h, then grouped and weighed.

After the feeding experiment, larvae were euthanized by freezing at -80 °C, then dried in an oven at 50°C for 48 h. The dried larvae were ground into a fine powder and stored in glass vials at -80°C. For extraction, 1g of dried larvae (in triplicate) was mixed with 10mL of n-hexane (Sigma, USA), homogenized (IKA, Germany), and subjected to ultrasonication (Wise Clean, Korea) at 100% power for 10 min. Extractions were performed at 25°C on a shaker (GFL Orbital Shaker 3005, Germany) at 250 rpm for 1 h. The mixture was then filtered through a single layer of filter paper followed by a 0.25µm syringe filter (Eppendorf, Germany). The resulting filtrates were evaporated using a rotary evaporator (Heidolph, Germany).

For chromatographic profiling, a 1µL portion of each extract was introduced via an autosampler into an Agilent 7890B gas chromatograph coupled to a mass spectrometer (Agilent Technologies, Santa Clara, CA, USA). Separation of constituents was carried out on a DB-5 MS capillary column (30m × 0.25mm, 0.25µm film thickness) using helium as the mobile phase at a constant flow of 1mL/min. The injector operated at 250°C in split mode with a 50:1 ratio. The oven temperature program ramped from 50°C to 250°C over a total run time of 71min. The mass spectrometer acquired data between m/z 40 and 500 at 1.56 scans per second, with a 4-min solvent delay and an ion source temperature of 230°C. Identification of detected compounds was performed by comparison with the NIST spectral database (Abutaha and Al-Mekhlafi, 2025).

All statistical analyses were conducted using the SPSS software package. The collected data were analyzed using one-way analysis of variance (ANOVA), and significant differences among the means were identified using Tukey's HSD post hoc test at a significance level of $P \leq 0.05$.

RESULTS

The survival of *T. molitor* larvae was monitored over a 6-week feeding trial across diets containing different proportions of *W. Filifera* (OPF) and wheat bran (WB). Larval survival remained high in all treatments during the first two weeks, with values ranging from 96.4% to 98.8%, and no significant differences were observed among diets (Table 1). By week 4, survival in the OPF-only diet declined to 81.25±2.43%, whereas all other treatments including mixed OPF–WB formulations and the wheat bran control maintained significantly higher survival rates (95.50–97.50%; $F = 16.502$, $p<0.05$). A similar pattern was observed at week 6: larvae fed exclusively on OPF exhibited the lowest survival (73.00±1.73%), while those provided with blended diets or wheat bran alone showed consistently high survival (89.00–96.50%; $F = 18.508$, $p<0.05$). Despite numerical differences, the overall analysis indicated that, with the exception of the OPF-only diet, supplementation of wheat bran with OPF at 25–75% did not negatively affect larval viability throughout the experimental period. These findings demonstrate that OPF can be incorporated into *T. molitor* diets at moderate levels without compromising survival.

The individual weight of *T. molitor* larvae was significantly influenced by the dietary ratio of *W. filifera* fruit powder (OBF) and wheat bran (WB) throughout the 2, 4, and 6-week feeding periods (Figure 1). After 2 weeks, larvae fed exclusively on OPF showed the lowest mean weight (–3.95 mg), a negative value indicating that larval weight had decreased below the initial starting weight. In contrast, WB-fed larvae reached the highest weight (21.61mg). The mixed diets (OPF75–WB25, OPF50–WB50, and OPF25–WB75) produced intermediate weights ranging from 16.26 to 22.74mg, with significant differences among treatments.

Table 1. Presents the survival percentages (±SE) of *Tenebrio molitor* larvae after being fed for six weeks with wheat bran (control) (WB 100) and bran supplemented with varying proportions of Ornamental palm fruits (OPF) 100, OPF 50-WB 50, and OPF 25-WB 75 (n = 5)

Diets	Survival (%)		
	two weeks	four weeks	six weeks
OPF	98.8 ± 0.8 [a]	81.25±2.43 [b]	73.00±1.73 [b]
OPF75 -WB25	98.8±0.49 [a]	96.50±1.26 [a]	95.00±1.29 [a]
OPF50 - WB50	98.4±.0.98 [a]	95.50±1.71 [a]	93.50±2.99 [a]
OPF25 -WB75	96.4±2.23 [a]	97.50±0.50 [a]	96.50±0.50 [a]
WB	98.8±0.49 [a]	94.50±1.71 [a]	89.00±3.32 [a]
dr	4	4	4
F	1.407	16.502	18.508

There are no statistically significant differences ($p < 0.05$). OPF = Ornamental palm fruits, WB= wheat bran.

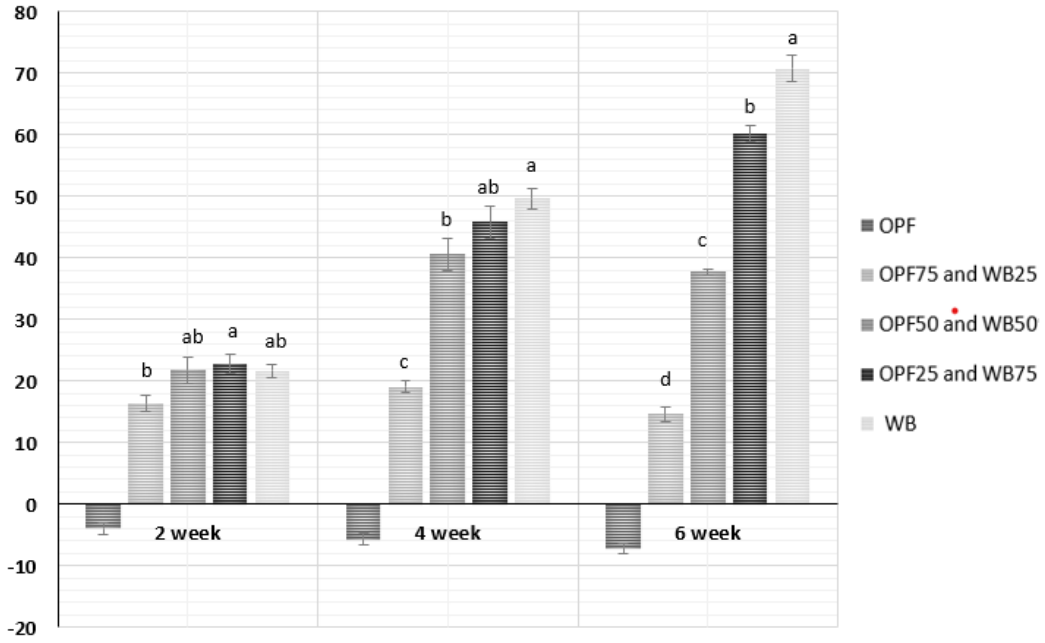


Figure 1. Individual weight (mg) of *Tenebrio molitor* larvae fed for six weeks with wheat bran (control) (OPF 0 WB 100) and bran fortified with different rates of Ornamental palm fruit (OBF 100-WB 0), OBF 50-WB 50 and OBF-25 WB 75 (n = 5).
Statistically significant differences ($p < 0.05$) are denoted with different superscript letters.
OBF= Ornamental palm fruit, WB= wheat bran,

After four weeks, larval weights increased across all treatments; however, OPF-fed larvae again exhibited negative growth (–5.70mg), confirming a continued decline relative to their initial weight. WB-fed larvae had the highest weight (49.58mg), while the mixed diets ranged from 19.07 to 45.77mg, with OPF25–WB75 and OPF50–WB50 statistically comparable to the control. By 6 weeks, WB-fed larvae reached the maximum weight (70.73mg), followed by OPF25–WB75 (60.09mg) and OPF50–WB50 (37.72mg). The OPF-only diet continued to yield negative growth (–7.20mg), indicating further weight loss relative to initial larval mass. Overall, larvae reared on wheat bran or bran-rich mixtures (WB ≥ 50%) consistently achieved

significantly higher body weights compared to larvae fed diets with high OPF content.

The weights of *T. molitor* pupae and adults were strongly influenced by the dietary proportions of Ornamental palm fruit (OPF) and wheat bran (WB) (Fig. 2). Pupal weights showed clear variation among treatments. Larvae reared on OPF alone did not develop successfully, resulting in a pupal weight of 0.00mg, indicating failure to reach the pupal stage. In contrast, the highest pupal weights (0.10g) were recorded for the mixed diets OPF75–WB25, OPF50–WB50, and OPF25–WB75. These values were statistically comparable to one another and similar to the pupal weight obtained on the WB control diet (0.09mg).

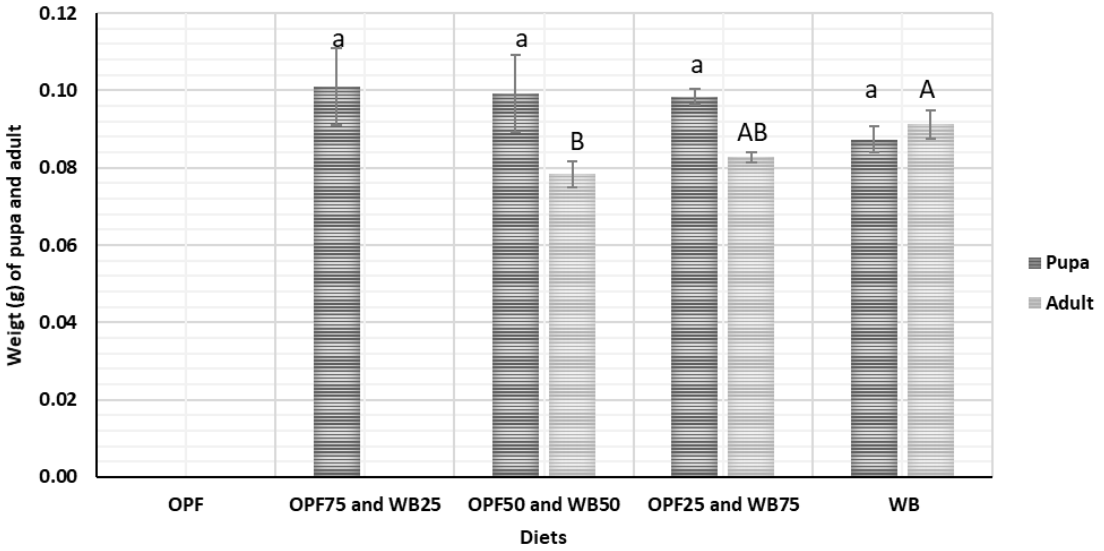


Figure 2. Pupal and adult weights of *Tenebrio molitor* reared on diets containing different proportions of Ornamental palm fruit (OBF) and wheat bran (WB). Bars represent the mean weight (mg) of pupae and adults (n = 5) fed OBF 100%, OBF75–WB25, OBF50–WB50, OBF25–WB75, or the control diet (WB 100%).
Different lowercase letters above pupal bars and uppercase letters above adult bars indicate statistically significant differences among diets ($p < 0.05$).

Adult weights followed a similar trend but showed stronger differentiation among diets. No adults emerged from larvae fed the OPF-only or OPF75–WB25 diets (0.00mg), reflecting poor development under high OPF content. Adults reared on OPF50–WB50 and OPF25–WB75 reached an average weight of 0.08g, forming an intermediate statistical grouping. The highest adult weight was recorded in the WB control diet (0.09g), which was significantly greater than the mixed diets and markedly higher than the OPF-only treatments.

Overall, the results indicate that diets containing moderate proportions of wheat bran (≥50%) are essential for normal pupal and adult development. Complete reliance on OPF or high-OPF mixtures severely inhibited both pupation and adult emergence, while mixed diets containing OPF25–75% supported pupal development comparable to the control but still produced lighter adults than WB alone.

GC-MS analysis of n-hexane extracts revealed that both WF 100 and OPF25:WB75 are dominated by polyunsaturated and saturated fatty acids, with 9,12-Octadecadienoic acid (Z,Z)- (linoleic acid) and n-Hexadecanoic acid (palmitic acid) as the principal components. Sample 5 contained 31 compounds, with the major constituents being linoleic acid (67.43%), n-Hexadecanoic acid (12.26%), Hexadecenoic acid, Z-11- (2.69%), and Tetradecanoic acid (2.50%), while Sample 2 contained 32

compounds, with linoleic acid (66.54%), n-Hexadecanoic acid (14.48%), Tetradecanoic acid (3.66%), and 2,6,10,14-Hexadecatetraen-1-ol, 3,7,11,15-tetramethyl-, acetate, (E,E,E)- (2.04%) as the major constituents. Minor components (<2%) in both samples included various fatty acids, esters, alcohols, squalene, and heptacosane. Comparative analysis showed that Sample 2 had a slightly higher proportion of palmitic acid (14.48% vs. 12.26%) and tetradecanoic acid (3.66% vs. 2.50%), whereas Sample 5 exhibited a slightly higher abundance of linoleic acid (67.43% vs. 66.54%). In addition, Sample 2 contained five compounds not detected in Sample 5 cis-Vaccenic acid, n-Propyl 11-octadecenoate, 9,12-Octadecadienoic acid (Z,Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester, Behenic alcohol, and Z,Z-3,15-Octadecadien-1-ol acetate—while Sample 5 had three exclusive compounds: 6-Octadecenoic acid, 12-Methyl-E,E-2,13-octadecadien-1-ol, and 1-Hexadecanol, 2-methyl.

Overall, these findings indicate that the phytochemical profiles of the two extracts are largely consistent, with linoleic acid as the dominant compound and minor variations in both the relative abundance of shared constituents and the presence of unique minor compounds (Tables 2 and 3).

Table 2. The percentage composition of fatty acids in mealworms extracted using n-hexane wheat bran (WB)

Peak	RT	Area%	Name of Compounds	MF	Mw
1	27.061	0.153396	Dodecanoic acid	$C_{12}H_{24}O_2$	200
2	31.21	0.081019	Methyl tetradecanoate	$C_{15}H_{30}O_2$	242
3	32.062	0.352027	E-9-Tetradecenoic acid	$C_{14}H_{26}O_2$	226
4	32.907	2.498389	Tetradecanoic acid	$C_{14}H_{28}O_2$	228
5	36.446	0.211568	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	270
6	37.348	2.688179	Hexadecenoic acid, Z-11-	$C_{16}H_{30}O_2$	254
7	38.358	12.26149	n-Hexadecanoic acid	$C_{16}H_{32}O_2$	256
8	40.436	0.820575	9,15-Octadecadienoic acid, methyl ester	$C_{19}H_{34}O_2$	294
9	40.621	1.133715	9-Octadecenoic acid (Z)-, methyl ester	$C_{19}H_{36}O_2$	296
10	41.242	0.060385	trans-13-Octadecenoic acid	$C_{18}H_{34}O_2$	282
11	42.953	67.42847	9,12-Octadecadienoic acid (Z,Z)-	$C_{18}H_{32}O_2$	280
12	43.248	0.23002	Oleic Acid	$C_{18}H_{34}O_2$	284
13	44.991	0.41779	cis-10-Nonadecenoic acid	$C_{19}H_{36}O_2$	296
14	46.273	0.154865	6-Octadecenoic acid	$C_{18}H_{34}O_2$	282
15	46.407	0.617296	9-Octadecenamide, (Z)-	$C_{18}H_{35}NO$	281
16	47.526	0.138417	10-Undecenoic acid, octyl ester	$C_{19}H_{36}O_2$	296
17	47.66	0.2777	8,11,14-Eicosatrienoic acid, (Z,Z,Z)-	$C_{20}H_{34}O_2$	306
18	48.453	0.199254	cis-13-Eicosenoic acid	$C_{20}H_{38}O_2$	310
19	48.59	0.905207	Glycidyl oleate	$C_{21}H_{38}O_3$	338
20	49.174	1.476348	Heptacosane	$C_{27}H_{56}$	380
21	50.101	1.716237	Erucic acid	$C_{22}H_{42}O_2$	338
23	51.122	0.128441	9-Octadecenoic acid (Z)-, 2-hydroxy- 1 (hydroxymethyl) ethyl ester	$C_{21}H_{40}O_4$	356
24	51.977	0.47167	Z-17-Nonadecen-1-ol acetate	$C_{21}H_{40}O_2$	324
25	52.998	0.376029	trans-9-Octadecenoic acid, pentyl ester	$C_{23}H_{44}O_2$	352
26	53.161	0.451079	Oleic acid, 3-hydroxypropyl ester	$C_{21}H_{40}O_3$	340
27	54.822	1.100293	12-Methyl-E,E-2,13-octadecadien-1-ol	$C_{19}H_{36}O$	280
28	56.771	1.250232	1-Hexadecanol, 2-methyl-	$C_{17}H_{36}O$	256
29	58.461	1.439729	2,6,10,14-Hexadecatetraen-1-ol, 3,7,11,15-tetramethyl-, acetate, (E,E,E)-	$C_{22}H_{36}O_2$	332
30	59.089	0.38194	Squalene	$C_{30}H_{50}$	410
31	60.245	0.578243	1-Heptacosanol	$C_{27}H_{56}O$	396

RT = Retention time (min); MW = Molecular weight (g/mol); MF = Molecular formula.

Table 3. The percentage composition of fatty acids in mealworms extracted using n-hexane OPF25 and WB75

Peak	Rt	Area%	Name of Compounds	MF	Mw
1	27.051	0.245791	Dodecanoic acid	$C_{12}H_{24}O_2$	200
3	31.207	0.054877	Methyl tetradecanoate	$C_{15}H_{30}O_2$	242
4	32.043	0.248989	E-9-Tetradecenoic acid	$C_{14}H_{26}O_2$	226
5	32.957	3.655958	Tetradecanoic acid	$C_{14}H_{28}O_2$	228
6	36.44	0.218071	Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	270
7	37.262	1.509693	Hexadecenoic acid, Z-11-	$C_{16}H_{30}O_2$	254
8	38.376	14.47966	n-Hexadecanoic acid	$C_{16}H_{32}O_2$	256
9	40.429	0.784485	9,15-Octadecadienoic acid, methyl ester	$C_{19}H_{34}O_2$	294
10	40.615	1.15407	9-Octadecenoic acid (Z)-, methyl ester	$C_{19}H_{36}O_2$	296
11	41.238	0.098145	trans-13-Octadecenoic acid	$C_{18}H_{34}O_2$	282
12	42.934	66.54349	9,12-Octadecadienoic acid (Z,Z)-	$C_{18}H_{32}O_2$	280
13	43.104	0.133919	cis-Vaccenic acid	$C_{18}H_{34}O_2$	282
14	43.261	0.279239	Oleic Acid	$C_{18}H_{34}O_2$	284
15	44.987	0.166135	cis-10-Nonadecenoic acid	$C_{19}H_{36}O_2$	296
16	46.407	0.782601	9-Octadecenamide, (Z)-	$C_{18}H_{35}NO$	281
17	47.523	0.107165	10-Undecenoic acid, octyl ester	$C_{19}H_{36}O_2$	296
18	47.655	0.271995	8,11,14-Eicosatrienoic acid, (Z,Z,Z)-	$C_{20}H_{34}O_2$	306
19	48.449	0.205999	cis-13-Eicosenoic acid	$C_{20}H_{38}O_2$	310
20	48.588	1.005057	Glycidyl oleate	$C_{21}H_{38}O_3$	338
21	49.175	2.010835	Heptacosane	$C_{27}H_{56}$	380
22	49.771	0.079103	Erucic acid	$C_{22}H_{42}O_2$	338
23	50.532	0.148351	n-Propyl 11-octadecenoate	$C_{21}H_{40}O_2$	324
24	51.119	0.189251	9-Octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester	$C_{21}H_{40}O_4$	356
25	51.856	0.138402	9,12-Octadecadienoic acid (Z,Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester	$C_{21}H_{38}O_4$	354
26	51.972	0.452412	Z-17-Nonadecen-1-ol acetate	$C_{21}H_{40}O_2$	324
27	52.982	0.624734	trans-9-Octadecenoic acid, pentyl ester	$C_{23}H_{44}O_2$	352
28	53.157	0.426349	Oleic acid, 3-hydroxypropyl ester	$C_{21}H_{40}O_3$	340
29	55.175	0.3014	Behenic alcohol	$C_{22}H_{46}O$	326
30	55.92	0.217822	Z,Z-3,15-Octadecadien-1-ol acetate	$C_{20}H_{36}O_2$	308
31	58.486	2.037831	2,6,10,14-Hexadecatetraen-1-ol, 3,7,11,15-tetramethyl-, acetate, (E,E,E)-	$C_{22}H_{36}O_2$	332
32	59.091	0.600523	Squalene	$C_{30}H_{50}$	410
33	60.244	0.827647	1-Heptacosanol	$C_{27}H_{56}O$	396

RT = Retention time (min); MW = Molecular weight (g/mol); MF = Molecular formula.

DISCUSSION

Insects are increasingly considered for use in animal feed because of their high protein and fat content. Their capacity to convert a wide range of organic residues into valuable biomass offers environmental benefits, aligning well with the principles of the circular economy. The usefulness of these by-products depends on how effectively the target livestock can utilize the resulting insect meal. Since insects efficiently transform feed into body mass, many types of agricultural leftovers can serve as suitable substrates for their rearing. This has encouraged extensive research into side-stream materials for cultivating yellow mealworms, as highlighted in the review by Van Peer *et al*. (Van Peer *et al.*, 2021).

The present study shows that the proportion of *W. filifera* fruit powder (OBF) used to replace wheat bran (WB) affects the growth and

development of *T. molitor*. Larvae fed diets with partial substitution of WB by OBF (25–75% OBF) achieved weights comparable to the control (WB 100), whereas full replacement with OBF (OBF 100%) produced significantly lower larval, pupal, and adult weights across the experimental period. This pattern indicates that moderate inclusion of OBF can be tolerated without major loss of performance, but complete replacement of wheat bran is nutritionally inadequate. Similar conclusions have been reported in studies testing partial replacement of bran with agro-food wastes: mixed diets often maintain growth performance, while extreme or single-ingredient diets can reduce performance (Li *et al.*, 2016; Morales-Ramos *et al.*, 2020; Rumbos *et al.*, 2022; Montalbán *et al.*, 2023)

Wheat bran is widely used as a standard rearing substrate for *T. molitor* because it provides a favorable balance of digestible energy, carbohydrates, and proteins and supports good growth, survival, and development in mealworms. Multiple experimental studies and reviews have found that wheat-bran-based diets frequently yield higher growth rates and better developmental outcomes than many alternative single-ingredient substrates (Riaz *et al.*, 2023, Al-Mekhlafi *et al.*, 2024). In our results higher weights in treatments with greater proportions of WB are consistent with these established findings.

W. filifera fruits and seeds contain carbohydrates, fiber, lipids, and a variety of bioactive compounds, but their macronutrient profile and digestibility differ from those of wheat bran. Nutritional surveys and phytochemical studies of *W. filifera* report appreciable fiber and bioactive content and indicate antioxidant and other bioactivities in seed extracts(Cornett, 1987, Uluçınar, 2017). Although the exact composition of our OBF batch was characterized, these compositional differences may partially explain the reduced insect performance observed when OBF fully replaced WB.

High dietary fiber and certain plant secondary metabolites are known to impair nutrient digestibility and slow growth in *T. molitor* and other insects, especially when included at excessive levels. Research consistently shows that fiber-rich or nutritionally unbalanced diets tend to produce smaller larvae, lighter pupae, and reduced adult mass, likely because these feeds provide less usable energy or interfere with normal nutrient absorption. This pattern was also documented by (Montalbán *et al.*, 2023) , who found that larvae fed diets made entirely from tigernut pulp (*Cyperus esculentus* L). or grape pomace (*Vitis vinifera* L.) grew more poorly than those raised on a standard wheat-bran diet. Similar findings from (Li *et al.*, 2016) and (Morales-Ramos *et al.*, 2020) indicate that high fiber levels can impose nutritional stress on yellow mealworms, ultimately reducing their growth performance. Therefore, the use of by-products at a full 100% inclusion rate appears to hinder larval development. The reduced weights observed in the 100% OBF treatment are most likely due to limited digestible protein and energy, as well as the presence of indigestible or anti-nutritional components in the fruit-derived material.

Conversely, partial inclusion of OBF (25–75% OBF) produced acceptable growth and development, suggesting that OBF has value as a supplement or co-ingredient. This pattern supports the broader literature that many agro-food wastes and by-products (spent grains, fruit/vegetable wastes, bakery residues, etc.) can be incorporated into mealworm diets at moderate levels to valorize waste streams while maintaining production performance provided the formulation supplies adequate protein, energy, and digestibility (Rashidi Ilzoleh and Akmali, 2025, Montalbán *et al.*, 2023).

Regarding survival, the present study showed that varying the proportions of WB and OPF in the diet did not cause any significant increase in larval mortality. Overall, the survival rates observed here were comparable to those reported in recent studies (Liu *et al.*, 2020, Ruschioni *et al.*, 2020, Riaz *et al.*, 2023), indicating that diet composition can substantially influence the life cycle of *T. molitor*, particularly in terms of growth, weight gain, and overall survival.

From a production perspective, partial substitution of wheat bran with *W. filifera* powder could reduce feed costs and support circular-economy goals by valorizing local palm fruit waste. However, because full substitution reduced growth and adult mass, we do not recommend using OBF as the sole substrate without further processing or supplementation.

Processing steps (protein enrichment, removal or reduction of indigestible fractions, or blending with high-protein sources) or adding small amounts of wet feed (vegetables) could improve digestibility and nutrient balance and should be tested. Such approaches have improved mealworm performance when other wastes were used as partial replacements (Montalbán *et al.*, 2023).

The GC–MS results of the control wheat bran (WB 100) extract and the mixed diet (OP25-WB75) provide additional evidence supporting the superior performance of larvae fed diets containing wheat bran, either alone or as the dominant ingredient.

The GC–MS analysis of extracts revealed that both samples were dominated by polyunsaturated and saturated fatty acids, with linoleic acid and palmitic acid as the major constituents. Linoleic acid (C18:2) was the most abundant compound in both samples 67.43% in WB and 66.54% in OP25-WB75 followed by palmitic acid, tetradecanoic acid, and a series of minor fatty acids, esters, and alcohols.

Fatty acids such as linoleic, palmitic, and oleic acids are known to be essential or highly beneficial for insect growth, energy metabolism, membrane development, and cuticle formation (Dreassi *et al.*, 2017; Kaczmarek *et al.*, 2024). Their presence in relatively high amounts is consistent with the generally good growth performance observed in *T. molitor* fed WB-based diets.

The slight differences in fatty acid abundance between the two samples such as the higher palmitic acid (14.48%) and tetradecanoic acid (3.66%) in OP25-WB75 and the higher linoleic acid in WB may help explain the modest but measurable variation in growth between the control and the 25% OBF–75% WB diet.

Like many other animals, yellow mealworms can store fat as an energy reserve. This means that they are not only a good source of protein but also a valuable source of dietary fat. Therefore, assessing the fat content of mealworm in relation to their diet is important. Some studies, such as those using olive pomace, have reported that larval fat content does not necessarily reflect the fat content of the feed (Ruschioni *et al.*, 2020). Other research has found more direct correlations. For example, Kotsou *et al*. (Kotsou , 2023) supplemented mealworm diets with orange albedoand observed that higher levels of albedo reduced larval fat, likely due to the albedo's low fat content. In our study, larvae fed OPF diets showed similar trends. Despite its high fiber content, the TP diet led to increased larval fat, likely because tigernut pulp itself is rich in fat. Additionally, Bordiean *et al*. (Bordiean *et al.*, 2022) reported that lower dietary protein can result in higher fat deposition in larvae, which is consistent with our observations. It has also been noted that diets high in protein and fat tend to improve various biological performance traits compared to carbohydrate-rich diets (Morales-Ramos *et al.*, 2013). In our experiments, GC–MS analysis also revealed unique compounds in each extract. OP25-WB75 included exclusive compounds such as cis-Vaccenic acid, n-Propyl 11-octadecenoate, behenic alcohol, and Z,Z-3,15-octadecadien-1-ol acetate molecules that may originate from the OBF fraction.

Thus, integrating the biological and chemical data provides a coherent explanation for the nutritional limitations of OBF as a primary feed substrate and reinforces the conclusion that while OBF can be used as a supplement, wheat bran should remain the major dietary component in *T. molitor* production.

CONCLUSION

The present study demonstrates that *W. filifera* fruit powder (OBF) can partially replace wheat bran in yellow mealworm (*T. molitor*) diets without compromising growth, development, or survival. Full substitution, however, reduces larval, pupal, and adult weights, likely due to lower digestible protein, energy, and the presence of indigestible or anti-nutritional compounds. GC–MS analyses indicate that fatty acids such as linoleic, palmitic, and oleic acids, abundant in wheat bran, support optimal growth and development. Overall, moderate inclusion of OBF represents a promising strategy to valorize local palm fruit waste within a circular economy framework, but wheat bran should remain the primary substrate. Future research should explore diet optimization, supplementation, and processing approaches to enhance the nutritional value of OBF-based feeds for mealworm production.

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CONTRIBUTORS

FA Alzahrani, FA Al-Mekhlafi: study conception, objective, methodology, data analysis, discussion, manuscript writing, and approval of the version to be published. N Abutaha , MA Wadaan: manuscript revision, funding acquisition, supervision, approval of the version to be published

DATA AVAILABILITY STATEMENT

The research data are available within the article itself.

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