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Influence of Feed Form on *Tenebrio molitor* L. Adults and Young Larvae Performance

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Abstract

Competitive industrial farming of *Tenebrio molitor* L. requires strategies aimed at reducing production costs and improving overall efficiency. Among variable costs, feed is one of the most significant components. Previous research has mainly focused on the nutritional composition of diets, the use of agri-food by-products, and the optimization of multicomponent formulations, sometimes administered in pelleted form during bioassays. However, knowledge about the influence of the administration form is scarce. This study investigated the effects of different feed forms—finely ground (<0.5 mm), coarsely ground (0.5–2 mm), and assembled (pellets, cookies, and crumbles)—on both adult and larval performance. Three feeds (wheat bran, brewer's spent grain, and chicken feed) were tested to assess adult productivity and larval growth. The results showed non-significant differences in adult survival between feed forms, whereas finely ground feed significantly increased adult productivity and the survival of newborn larvae. Furthermore, larvae in the growing phase (40–60 days old) were able to effectively utilize assembled feeds, with no significant differences in larval weight compared to those reared on ground diets. These findings suggest that pelleted formulations for *T. molitor* farming should include a fraction of finely ground material to support early larval stages, thereby optimizing survival and development. Moreover, the different influence of feed form provides useful information for planning evaluation trials of multicomponent assembled diets.

Keywords: mealworm; pellet; rearing insect; diet size; wheat bran; brewer's spent grain; productivity; assembled feed

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1. Introduction

Insect farming for food and feed production is considered a more sustainable alternative to conventional livestock farming [1,2]. Insects have the capacity to bioconvert agri-food by-products and potential waste streams into valuable outputs such as proteins, lipids, chitin, and fertilizers, which promotes the resilience of the food system and aligns with the principles of the circular economy [3–5]. In particular, the bioconversion of waste by insects represents an ecosystem service that helps close nutrient loops and contributes to resource efficiency [6]. Despite this potential, the sector still faces legislative obstacles that limit the use of certain by-products as substrate, although significant regulatory advancements have occurred in recent years [7]. From an economic perspective, the viability of industrial insect farming depends on reducing production costs while improving process knowledge and efficiency, regardless of the intended application, whether for novel food, protein-reach feed, lipids for feed or biofuel, or fertilizer production [8]. In the case of *Tenebrio molitor* L. (Coleoptera: Tenebrionidae), several knowledge gaps persist regarding the optimization of large-scale rearing techniques, diet formulations, and the valorization of its by-products, particularly frass as fertilizers [9]. Diets represent one of the major variable costs in mealworm production and play a central role in determining the economic sustainability of farming systems [10].

To develop cost-effective diets, numerous studies have tested various feed ingredients, agri-food by-products, either as single components or in multicomponent formulations, often used in mixtures or as alternatives to wheat bran [11–14]. Other research efforts have focused on improving the nutritional quality of the larvae through specific diets. In this regard, the fatty acid composition (such as SFA, PUFA percentages, and n-6/n-3 ratio) was found to be more suitable for foods intended for humans [15–17]. Similarly, mealworm flours with higher antioxidant content have been obtained from diets of larvae reared on diets based on orange processing residues, distillery by-products, and former foodstuffs [18–20]. However, although lower-cost diets may offer economic advantages, they must still ensure larval growth performance at least equivalent to that of the standard reference diet.

Nutritionally efficient diets for insects are often based on multicomponent formulations, in which different ingredients are combined in proportions that satisfy the target nutrient composition. To achieve this, several researchers have applied the nutritional geometry framework to optimize dietary profiles of *T. molitor* [21] and *Gryllodes sigillatus* (Walker) [22]. Other studies have leveraged the self-selection behavior of certain insect species to preliminarily determine the optimal composition of new diets. Self-selection is the ability of the insect to choose and eat its preferred portion within a mixed feed. This behavior is known in *T. molitor* [23,24], *Grillus bimaculatus* (de Geer) [25], and *Acheta domesticus* L. [26]. However, self-selection also represents a potential methodological limitation when evaluating mixed diets provided ad libitum in bulk form. On the contrary, the administration of new assembled diets reduces self-selection and facilitates the separation of frass and unconsumed feed, which is essential for accurately calculating of diet efficiency indices [17,27,28].

So far, the physical characteristics of Tenebrionidae's diet have received limited attention, with the few existing studies focusing primarily on the particle size [29,30]. Nonetheless, previous observations have demonstrated that a higher proportion of cracked wheat can positively affect the population growth of *Alphitobius diaperinus* (Panzer) [31]. In several studies on Tenebrionidae, pelleted feed was employed for purposes other than nutritional evaluation, such as reducing dust levels in mealworm farming [32], standardizing fermented diets [33], and developing formulations containing mycoinsecticides for the control of *A. diaperinus* [34].

To our knowledge, no comparative studies have evaluated the effects of different physical forms of diet administration, particularly in relation to powdered versus assembled feeds.

The pelletization process is widely used in animal feed production; however, it requires access to specialized industrial facilities. Generally, in laboratory tests, the feed is assembled manually and dried at low temperatures to prevent the degradation of thermolabile nutraceutical compounds. Various techniques have been employed to produce assembled feeds, including "extruded" forms [28], "short, thin strips" [27], and "cookies" [17]. The objectives of this study were to (1) evaluate the influence of ground and assembled feeds (pellets and cookies) on adult productivity, larval performance, and feed efficiency; and

(2) compare the effects of crumbled versus powdered chicken feed on adult productivity and larval growth under laboratory conditions, simulating a large-scale production system. A deeper understanding of how feed physical form influences performance could support more precise diet formulation and enhance the efficiency of mass-rearing *T. molitor*.

2. Materials and Methods

2.1. Diet Preparation

Soft wheat bran (W) and brewer's spent grain (B) were selected as the two basal substrates tested in two independent trials in the year 2024. Pelleted wheat bran (protein 15.0% on dry matter) was supplied by CESAC s.c.a. (Conselice, RA, Italy), with pellets measuring 8–12 × 6 mm (l × Ø). Pelleted brewer's spent grain (protein 18.7% on dry matter) was supplied by VIGORI (Kaunas, Lithuania), with pellets measuring 8–15 × 6 mm (l × Ø). For each substrate, four different physical feed forms were prepared by grinding the pellets and sieving them using 2 mm and 0.5 mm mesh manual sieves (Giuliani Tecnologie S.r.l. Torino, TO, Italy). Particles < 0.5 mm (PW) and 0.5–2 mm (GR) were used as ground feed forms, whereas the original unground pellets (PE) represented the assembled feed form. A fourth feed form was obtained by mixing PW and GR in a 50:50 (*w*/*w*) ratio to produce "cookies" (CO) measuring 10 × 10 × 2 mm (l × w × h), according to the method described by Baldacchino et al. [17]. The 0.5–2 mm ground fraction was used as a control feed in both the wheat bran and the brewer's spent grain trials.

A trial was set up in 2025 to test a smaller pellet size. In this trial, crumbled chicken feed (size 2–3 mm; NATURA VERA, Corato, BA, Italy) was used as the assembled feed form, while the same feed was ground and sieved (<0.5 mm) to obtain its powdered form.

2.2. Insect and Experimental Design

Tenebrio molitor L. individuals were obtained from the colony maintained at the *insectarium* of CIHEAM-Bari (Apulia region, Valenzano, Italy) and reared in a climatic chamber at 28 ± 1 °C, 60 ± 5% relative humidity (RH), and under a 0L:24D photoperiod. The colony was fed *ad libitum* on wheat bran and yeast (ratio 95:5 *w*/*w*), and pumpkin pieces were provided twice a week as a wet source.

Prior to the adult bioassay, pupae were sexed [35] under a stereoscope (mod. SMZ745T, Nikon Europe B.V., Amstelveen, The Netherlands) and stored separately for sex until adult emergence. Groups of five males and five females (per replicate) were placed in plastic cups (13 × 7 cm, h × Ø) containing 5 g of specific feed form to be tested. Pumpkin was added as a water source two to three times per week. The experimental design included ten replications/feed forms in a completely randomized design. Every ten days for seven consecutive intervals, live adults were counted and transferred to new cups containing fresh feed. Adult productivity was verified on the 30th post-oviposition day by counting the number of live larvae per replicate produced by live females during the specific oviposition time [36].

Subsequently, the first two oviposition events were used as two blocks to evaluate the performance of the young larvae. For this purpose, four times every 10 days, each replicate was weighed, and the value was divided by the number of live larvae. Additional feed was weighed and provided, when necessary, while 5 g of pumpkin was provided every three days, and any uneaten pumpkin was removed. On the 70th post-oviposition day, the experiment was terminated, and uneaten feed and frass were collected and weighed.

Survival (Equation (1)) and efficiency indices (Equations (2) and (3)) were calculated [37] using

$$\text{Survival (\%)} = \text{n. initial adults or larvae/n. final adults or larvae} \times 100 \quad (1)$$

$$\text{FCR (Feed Conversion Ratio)} = \text{FC/WG} \quad (2)$$

where FC represent the feed consumption (mg larvae^{-1}), and WG represents the larval gained weight at the end of the experiment;

$$\text{ECI (Efficiency of Conversion of Ingested feed)(\%)} = [\text{WG/FC}] \times 100 \quad (3)$$

For the third test, groups of 100 adults per replicate were placed in trays (9 × 11 cm) containing 100 g of specific feed form. The experimental design consisted of ten replicates per feed form in a completely randomized design. Adults were allowed to oviposit for seven days and then removed from the trays. On the 60th and 90th days after oviposition, the influence of feed form was verified by counting the number of live larvae, the larval weight, and the larval biomass.

2.3. Statistical Analysis

The data were subjected to homogeneity and normality tests. When these criteria were satisfied, a one-way ANOVA, repeated-measures ANOVA, and Tukey–Kramer HDS test post hoc were applied. When the criteria were not met, the Kruskal–Wallis test followed by pairwise multiple comparisons with Bonferroni correction was used. The *t*-test was applied to the data from the third trial to compare the two chicken feed forms. Significance was assumed at $p < 0.05$. Data were statistically analyzed using SSPS software version 26.0 (IBM Corporation, Armonk, NY, USA) and Microsoft® Excel® for Microsoft 365 MSO.

3. Results

The results of the trials with wheat bran and brewer's spent grain are shown in parallel, while the last section is dedicated to the results of the trial with chicken feed.

3.1. Effect on Adults' Productivity

Adult survival showed a similar decreasing trend across all tested feed forms and feed types (Figure 1). Throughout the observation period, no significant differences were detected between feed forms, either for wheat bran (with a minimum value of $p = 0.398$ at T10) or for brewer's spent grain (with a minimum value of $p = 0.063$ at T60).

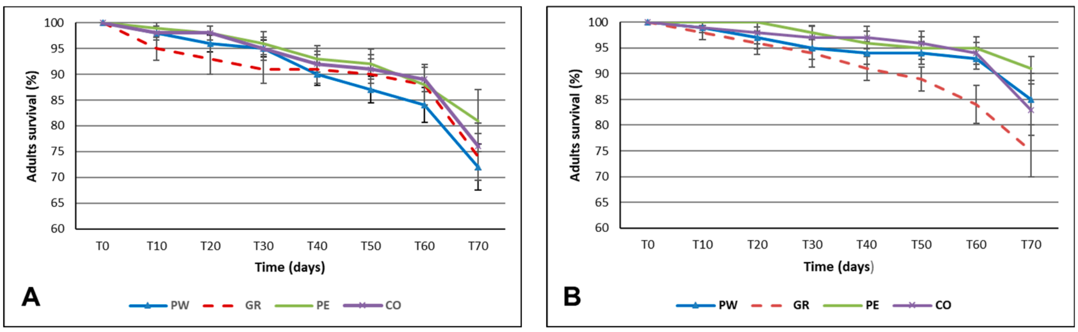

Figure 1. Adults' survival trends on different feed forms: (**A**) wheat bran; (**B**) brewer's spent grain. Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values ($n = 10$) with the same letter between feed forms are not significantly different (Kruskal–Wallis and pairwise multiple comparisons with Bonferroni correction) at $\alpha = 0.05$. The absence of letters indicates no difference between treatments.

Adult productivity, expressed as the mean number of larvae produced every 10 days, differed significantly among wheat bran feed forms ($F = 26.78$; df = 3, 36; $p < 0.001$). Adults reared on the two ground feed forms (PW and GR) produced approximately twice as many larvae as those on assembled forms (PE and CO) (Table 1). Similar results were also obtained with brewer's spent grain (F = 137.79, df = 3, 36; p < 0.001). In this case, however, the mean number of larvae obtained in PW was significantly higher than in the GR form (Table 1).

Table 1. Average production of larvae/live female on different forms of feed.

Feed Form [1]	n. Larvae/Live Female (Average Each Ten Days)	
	Wheat Bran	Brewer's Spent Grain
PW	22.8 ± 1.0 [a]	38.8 ± 1.3 [A]
GR	21.2 ± 0.5 [a]	19.5 ± 0.8 [B]
PE	10.6 ± 0.8 [b]	10.7 ± 0.8 [C]
CO	11.8 ± 0.7 [b]	8.1 ± 0.4 [C]

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 70) with the same letters within columns (same feed) are not significantly different (repeated-measure AVOVA and Tukey–Kramer HDS test) at α = 0.05.

The differences in larvae produced/live female were constant across oviposition. For wheat bran, with the exception of the first oviposition, the subsequent six ovipositions always confirmed a significantly higher number of larvae produced in the ground feed forms compared to the assembled ones (Table 2).

Table 2. Production of larvae/live females on different feed forms of wheat bran, in different oviposition times, and total quantities.

Feed Form [1]	T0–T10	T11–T20	T21–T30	T31–T40	T41–T50	T51–T60	T61–T70	T0–T70
PW	21.4 ± 2.2	27.1 ± 2.7 [a]	17.2 ± 1.5 [b]	17.6 ± 1.3 [b]	25.9 ± 3.0 [a]	27.1 ± 1.9 [a]	23.6 ± 4.2 [a]	159.8 ± 14.4 [a]
GR	21.6 ± 1.2	22.2 ± 1.6 [a]	21.4 ± 1.2 [a]	22.1 ± 1.7 [a]	19.1 ± 1.2 [b]	21.3 ± 1.2 [b]	20.4 ± 1.7 [ab]	148.1 ± 5.1 [a]
PE	21.3 ± 2.2	6.5 ± 0.9 [c]	6.1 ± 0.8 [c]	5.4 ± 0.9 [c]	11.8 ± 1.9 [c]	9.5 ± 1.6 [c]	13.6 ± 1.3 [bc]	74.1 ± 6.8 [b]
CO	20.7 ± 1.8	15.5 ± 1.5 [b]	8.7 ± 0.7 [c]	8.6 ± 0.7 [c]	11.9 ± 1.0 [c]	9.0 ± 0.9 [c]	8.1 ± 0.7 [c]	82.4 ± 3.4 [b]

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 10) with the same letter within columns are not significantly different (AVOVA and Tukey–Kramer HDS test) at α = 0.05. Where no letters exist, no significant differences were observed.

The productivity results for brewer's spent grain also confirmed the differences observed between feed forms in wheat bran; the significant differences in larvae produced/live female between ground and assembled feed forms were substantially confirmed throughout the entire oviposition period, from the first to the last period. Furthermore, the number of larvae recorded on PW was consistently higher and increasing over time compared to other feed forms (Table 3).

Table 3. Production of larvae/live females with different feed forms of brewer's spent grain, with different oviposition times and total quantities.

Feed Form [1]	T0–T10	T11–T20	T21–T30	T31–T40	T41–T50	T51–T60	T61–T70	T0–T70
PW	29.4 ± 2.2 [a]	32.4 ± 2.6 [a]	29.9 ± 2.2 [a]	41.3 ± 2.2 [a]	40.0 ± 1.9 [a]	46.7 ± 2.0 [a]	51.8 ± 2.5 [a]	271.3 ± 12.2 [a]
GR	17.3 ± 1.1 [b]	15.1 ± 1.0 [b]	16.0 ± 1.8 [b]	25.0 ± 1.6 [b]	19.8 ± 2.3 [b]	22.4 ± 2.6 [b]	21.2 ± 2.8 [b]	136.7 ± 9.8 [b]
PE	21.4 ± 2.2 [b]	8.1 ± 0.8 [c]	3.2 ± 0.5 [c]	7.9 ± 0.8 [c]	7.8 ± 1.0 [c]	11.8 ± 0.8 [c]	14.8 ± 1.3 [b]	74.9 ± 2.8 [c]
CO	10.3 ± 1.1 [c]	7.4 ± 0.7 [c]	3.9 ± 0.5 [c]	10.7 ± 1.2 [c]	9.9 ± 1.2 [c]	7.2 ± 1.0 [c]	6.9 ± 0.7 [c]	56.4 ± 4.7 [c]

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 10) with the same letter within columns are not significantly different (AVOVA and Tukey–Kramer HDS test) at α = 0.05.

The best results obtained with the ground feed forms were therefore validated by the overall temporal stability of the differences between the feed forms, as well as by their substantial confirmation on both tested diets.

3.2. Effect on Young Larvae

The survival of young larvae (considering the period from the 30th to the 70th day post-oviposition) ranged from 92.1 to 97.2% and 95.2 to 98.0% in wheat bran and brewer's spent grain, respectively (Table 4). Statistical analysis showed significant differences between feed forms of wheat bran (H = 17.79; df = 3; p < 0.001), with significantly lower survival values recorded for the CO form. Conversely, the different feed forms of brewer's spent grain did not significantly influence the survival of young larvae (H = 7.09; df = 3; p = 0.069) (Table 4).

Table 4. Survival of young larvae (calculated at end of 30th–70th day post-oviposition).

Feed Form [1]	Larval Survival (%)	
	Wheat Bran	Brewer's Spent Grain
PW	97.2 ± 0.7 [a]	95.2 ± 0.9
GR	96.4 ± 0.9 [a]	98.0 ± 0.7
PE	97.0 ± 1.4 [a]	96.0 ± 1.1
CO	92.1 ± 1.6 [b]	95.7 ± 2.1

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 20) with the same letter within columns are not significantly different (Kruskal–Wallis and pairwise multiple comparisons with Bonferroni correction) at α = 0.05. Where no letters exist, no significant differences were observed.

The influence of the different feed forms was also evident on larval growth. On wheat bran, the weight of larvae fed on PW, GR, and PE feed forms was significantly greater than that of larvae fed on the CO feed form in all measurements (Table 5). Furthermore, larval weight never differed significantly among the first three feed forms.

Table 5. Larval weight (mg of fresh weight) at different ages fed wheat bran (40th–70th day post-oviposition).

Feed Form [1]	Wheat Bran			
	40th Day	50th Day	60th Day	70th Day
PW	2.4 ± 0.1 [a]	10.2 ± 1.4 [a]	17.4 ± 1.7 [a]	23.8 ± 1.7 [a]
GR	2.5 ± 0.1 [a]	7.5 ± 0.3 [a]	14.6 ± 0.7 [a]	19.3 ± 0.9 [a]
PE	2.2 ± 0.2 [a]	7.6 ± 0.6 [a]	16.0 ± 1.0 [a]	25.2 ± 1.9 [a]
CO	1.5 ± 0.1 [b]	3.0 ± 0.1 [b]	5.2 ± 0.3 [b]	8.8 ± 0.5 [b]

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 20) with the same letter within columns are not significantly different (Kruskal–Wallis and pairwise multiple comparisons with Bonferroni correction) at α = 0.05.

For brewer's spent grain, the results at day 40 and 50 showed significantly heavier larvae when fed on the two ground forms (PW and GR) compared to the two assembled forms (PE and CO) (Table 6). From day 60 onward, only the GR feed form showed significantly heavier larvae; however, at the subsequent survey, the weight did not differ significantly between those fed on the GR and PE feed forms. Thus, in the case of the brewer's spent grain, the GR feed form consistently produced heavier larvae.

3.3. Efficiency Indicators

The feed conversion rate (FCR) was not significantly different between feed forms of wheat bran (F = 1.32; df = 3, 79; p = 0.274), but significantly different values were observed for brewer's spent grain (F = 23.67; df = 3, 79; p < 0.001) (Table 7). In the latter case, the highest values were recorded in PW and CO, and the lowest in GR and PE. Finally, the efficiency of conversion of ingested feed (ECI) was also not significantly different between feed forms for wheat bran (F = 1.74; df = 3, 79; p = 0.167), whereas significant differences were found for brewer's spent grain (F = 29.39; df = 3, 79; p < 0.001). The highest efficiency (ECI 39.6%) was achieved with the GR feed form, while lower efficiencies (30.3% and 30.4%, respectively) were recorded for PW and CO for brewer's spent grain (Table 7).

Table 6. Larval weight (mg on fresh weight) at different ages fed brewer's spent grain (40th–70th day post-oviposition).

Feed Form [1]	Brewer's Spent Grain			
	40th Day	**50th Day**	**60th Day**	**70th Day**
PW	2.9 ± 0.1 ^{a}	8.0 ± 0.3 ^{a}	13.0 ± 0.7 ^{b}	14.9 ± 1.0 ^{b}
GR	3.0 ± 0.2 ^{a}	9.0 ± 0.3 ^{a}	17.5 ± 0.7 ^{a}	22.2 ± 1.0 ^{a}
PE	1.9 ± 0.1 ^{b}	5.9 ± 0.2 ^{b}	10.7 ± 0.5 ^{b}	17.6 ± 0.9 ^{ab}
CO	2.0 ± 0.1 ^{b}	5.4 ± 0.2 ^{b}	10.2 ± 0.6 ^{b}	14.7 ± 0.7 ^{b}

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). The mean ± standard error values (n = 20) with the same letter within columns are not significantly different (Kruskal–Wallis and pairwise multiple comparisons with Bonferroni correction) at α = 0.05.

Table 7. Efficiency indicator of feed and feed form tested.

Feed Form [1]	Wheat Bran		Brewer's Spent Grain	
	FCR	**ECI (%)**	**FCR**	**ECI (%)**
PW	3.3 ± 0.1	30.9 ± 1.2	3.4 ± 0.2 ^{a}	30.3 ± 1.3 ^{c}
GR	3.2 ± 0.1	32.0 ± 0.9	2.5 ± 0.0 ^{b}	39.6 ± 0.6 ^{a}
PE	3.4 ± 0.1	29.8 ± 0.6	2.8 ± 0.1 ^{b}	36.3 ± 1.0 ^{b}
CO	3.4 ± 0.1	30.1 ± 0.8	3.3 ± 0.1 ^{a}	30.4 ± 0.7 ^{c}

[1] Feed form: PW (size < 0.5 mm); GR (size 0.5–2.0 mm) as control; PE (pellet); CO (cookie). Efficiency indicators: FCR (feed conversion rate); ECI (efficiency of conversion of ingested feed). The mean ± standard error values (n = 20) with the same letter within columns are not significantly different (AVOVA and Tukey–Kramer HDS test) at α = 0.05. Where no letters exist, no significant differences were observed.

3.4. Comparison of Chicken Feed Forms

The use of crumbled chicken feed, equivalent to very small pellets, provided significantly different performances compared to the same feed in powdered form (Figure 2A,B).

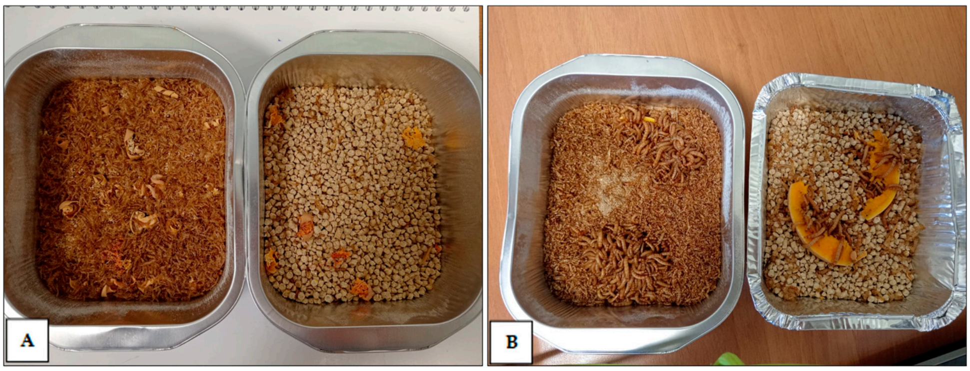

Figure 2. Comparison of chicken feed form at 60 days (**A**) and 90 days post-oviposition (**B**). The powdered form (tray on the **left**) shows an abundance of exuviae (at day 60) and larvae (at day 90) compared to the crumbled feed (tray on the **right**).

At day 60 after oviposition, adult productivity (expressed as the number of larvae per replicate) was significantly higher in the powdered feed form; in fact, the number of larvae was 2.7 times greater than in the crumbled form (Table 8). The effect was also positive for larval growth, as larval weight was significantly higher in the powdered feed form, with 19.4 mg/larva compared to 9.3 mg/larva in the crumbled feed form. Consequently, larval biomass was 5.6 times higher in the powdered feed form compared to the crumbled feed form (Table 8).

Table 8. Productivity at 60 days post-oviposition for different chicken feed forms.

Feed Form [1]	Larvae/Replicate (n.)	Larval Weight (mg)	Biomass/Replicate (g)
Powdered feed	646.6 ± 70.2 [a]	19.4 ± 0.6 [a]	12.3 ± 1.1 [a]
Crumbled feed	241.5 ± 19.5 [b]	9.3 ± 0.3 [b]	2.2 ± 0.1 [b]

[1] Feed form: powdered feed (size < 0.5 mm); crumbled feed (size 0.5–2.0 mm). The mean ± standard error values (n = 10) with the same letter within columns are not significantly different (t-test) at $\alpha = 0.05$.

A second evaluation carried out on the 90th day after oviposition confirmed the previous differences in the number of larvae/replicate; furthermore, during the last 30 days larval survival was high, at 98.6% and 99.2%, respectively, for the powdered and crumbled feeds (Table 9). Conversely, larval weight was no longer significantly different between feed forms; in the last 30 days, larvae fed powdered feed increased their weight by 2.54 times compared to 4.34 times for larvae fed crumbled feed. However, larval biomass remained significantly different between feed forms, with values 3 times higher for the powdered feed than for the crumbled one (Table 9).

Table 9. Productivity at 90 day post-oviposition for different chicken feed forms.

Feed Form [1]	Larvae/Replicate (n.)	Larval Weight (mg)	Biomass/Replicate (g)
Powdered feed	637.6 ± 69.1 [a]	49.2 ± 5.4	28.5 ± 0.2 [a]
Crumbled feed	239.5 ± 19.8 [b]	40.4 ± 1.7	9.4 ± 0.5 [b]

[1] Feed form: powdered feed (size < 0.5 mm); crumbled feed (size 0.5–2.0 mm). The mean ± standard error values (n = 10) with the same letter within columns are not significantly different (t-test) at $\alpha = 0.05$. Where no letters exist, no significant differences were observed.

4. Discussion

One technique for rearing mealworms involves the oviposition of adults into feeding trays where the larvae subsequently develop [38]. Therefore, our study addressed the practical need to evaluate different feed forms administered during the oviposition phase.

Our results consistently demonstrated that adult survival was not affected by the different feed forms for any of the three feeds tested.

Productivity was higher in ground (PW and GR) than in assembled (PE and CO) feeds, both for wheat bran and brewer's spent grain. This result was also confirmed by the third test, which compared powdered and crumbled chicken feed.

In previous studies, adult productivity of *T. molitor* was investigated by comparing different feeds and their mixtures, whereas evaluations of the influence of the feed forms are lacking [39–41].

In our experiments, productivity was assessed as the number of young larvae produced per female. However, this method is based on the direct correlation between the number of eggs produced and the number of larvae [36]. This represents a practical approach for production purposes but does not allow for the determination of the effects on oviposition or egg-larva survival. Oviposition is known to be negatively affected by low diet quality [42] and high adult density [43]. However, these influences should have been absent in our study, since the different feed forms were obtained from the same pelleted feed, and adult density was kept constant across feed forms. Egg loss can be caused by adult cannibalism, which, together with larval cannibalism of pupae, leads to reduced productivity in rearing farms [44–46]. Egg cannibalism is favored with high adult density and longer residence times in the oviposition trays [36]. To reduce egg loss due to cannibalism, density-to-oviposition times ratios were optimized [44]. Nevertheless, we believe that the number of viable eggs in our study is lower than that under optimal oviposition conditions. However, to the best of our knowledge, no studies have investigated the influence of particle size or feed form on cannibalism, so we can only hypothesize that eggs laid on aggregate feed are more easily identified and consumed by adults, and more susceptible to external environmental conditions and microorganisms. Compared with this hypothesis, we consider it more likely that ground feed enhances the survival of newly hatched larvae, which may have greater difficulty feeding on larger or aggregated feeds. However, this difficulty should occur within the first week of life, since survival did not differ when using 5-day-old larvae on milled bran of different sizes [30]. The initially lower access to the aggregated feed is supported by our results on the survival and weight of young larvae. Both the number of live larvae and their weight were significantly and consistently lower in aggregate feed than in ground feed. Although our experiments compared feed forms rather than feed types, this result was consistently observed at each oviposition in wheat bran and in brewer's spent grain (larvae one month old), as well as in chicken feed (larvae two months old). These findings agree with Zhong et al. [47], who demonstrated greater cumulative consumption of smaller-sized microplastics by one-month-old mealworms compared to larger-sized microplastics.

After 30–70 days from oviposition, the different wheat bran feed forms did not affect larval survival or weight gain, except for the lower performance observed with the feed assembled in "cookie" form. In brewer's spent grain, survival was unaffected, while larval weight was lower in both assembled forms up to day 50. Subsequently, the results showed a different growth pattern: larvae were lighter in PW and CO than in GR (control), while the weight of those fed PE was not significantly different from that of those fed GR (at day 70). This change in performance between powdered and pelleted feeds was also confirmed by the weight recovery of larvae fed with crumbled chicken feed between the 60^{th} and 90^{th} day. The possible different influence of the feed agrees with observations made with equal particle sizes in previous studies on *T. molitor* [29]. Our results confirm the general suitability of ground feed (particle size of 0.5–2 mm) and support the hypothesis that larger larvae can feed on larger particles. This hypothesis is also supported by the better weight gain observed for finer feed in small *A. diaperinus* larvae compared to larger *T. molitor* larvae [30]. The relationship between insect size and feed particle size has also been shown in *A. domesticus*, with development positively correlated between strains of different sizes and the size of the feed provided [48]. In *Teleogryllus occipitalis* (Audinet-Serville), a granular diet promoted better growth than a powdery one [49], and in choice tests, *G. sigillatus* preferentially consumed particles of 1.0–1.4 mm compared to smaller particles [50]. Furthermore, previous authors have suggested that these effects are limited to the early growth period, since final results tend to be the same, in agreement with our results for crumbed chicken feed [30,50]. Therefore, assembled feeds (pellet, cookie, and crumble) can be initially equated to large particles, although some factors (such as feed type, compactness, and hygroscopicity) and the pelletizing process affect their integrity over time [51].

The FCR and ECI efficiency indices were similar between wheat bran feed forms and aligned with those detected in milled bran by Bailota et al. [30]. Conversely, the brewer's spent grain showed higher FCR values (therefore lower efficiency) when pulverized and assembled into cookies. The cause of this could be the greater presence of raw fiber and lignin (fragments of glumes) in the brewer's spent grain compared to the wheat bran [52], which, if ingested, can reduce digestibility [53]. Therefore, we hypothesize that the larvae do not select but ingest the too small fragments of glume present in the pulverized feed, as already verified with cellulose [54]. Similarly, the larvae would ingest the small fragments incorporated into the cookies, since these were assembled with 50% feed particles smaller than 0.5 mm. In contrast, larvae can self-select ground feed (0.5–2 mm) and later also select disintegrated pellets.

Unfortunately, the lack of previous studies on assembled feed does not allow for a further comparison of our results, and many knowledge gaps remain.

Thus, our results provide important input for optimizing the feed administration format in *T. molitor* farming. Hypothetically, a new diet formulation could include a mixed portion of ground and powdered feed (essential during the oviposition and development of newborn larvae) and a portion of assembled feed as pellet/crumble (usable by larvae one to two months old). In this case, specific studies would be necessary to test its effectiveness. The results obtained also contribute to improving experimental methodologies aimed at verifying the efficiency of multicomponent diets, administered in assembled form to avoid self-selection. In this case, assembled diets should be tested on growing larvae (40–60 days old), avoiding the use of younger or newborn larvae.

5. Conclusions

Our results highlight that ground feed is essential for the optimal oviposition phase of *T. molitor*, as it increases larval/female productivity. Growing larvae (over 40–60 days old) can utilize assembled feed (pellets, biscuits, and crumbles) as efficiently as ground feed. This utilization capacity increases as the larvae grow and tends to produce similar final larval weights with both feed forms. These inputs suggest that multicomponent diets can also be optimized in their delivery form.

Finally, this new knowledge also represents useful information for planning evaluation trials of multicomponent diets. The use of assembled diets to avoid self-selection should be reserved only for larvae over 40–60 days of age.

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Abbreviations

The following abbreviations are used in this manuscript:

SFA	Saturated Fatty Acid.
PUFA	Polyunsaturated Fatty Acid.
W	Wheat bran.
B	Brewer's grain spent.
PW	Powered form.
GR	Ground form.
PE	Pelleted form.
CO	"Cookie" form.

FCR	Feed Conversion Rate.
SGR	Specific Growth Ratio.
ECI	Efficiency of Conversion of Ingested Feed.

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