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Growth and reproductive performance of American cockroach (*Periplaneta americana*) as affected by photoperiod and feed type

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Abstract
American cockroach is a reliable source of protein as an animal feed but remains unexploited. Little is known on the right combination of environmental factors for their mass production under artificial conditions. This study assessed the effect of photoperiod and feed as key factors in cockroach rearing on their growth and reproductive performance. Factorial experiment with two factors: photoperiod at four levels; 3L:21D, 6L:18D, 12L:12D, and 18L:6D, and feed at two levels (Chick mash, and chick mash + carrot) was designed. The experiment was laid in a split-plot design with photoperiod as the main plot factor and feed as the sub-plot factor. Measurements were taken on a weekly basis for growth parameters (body mass, body length and cephalic length), and reproductive parameters (length of the ootheca, number of eggs per ootheca and weight of the ootheca) throughout the feeding period. Photoperiod significantly affected the body mass ($p<0.000$) and cephalic length ($p=0.006$) of the cockroaches but insignificantly affected their reproductive parameters. Feed type did not have significant effect on both the growth and reproductive performance of the cockroaches. However, photoperiod and feed interaction had significant positive effect on the growth parameters of the cockroaches but insignificantly affected the reproductive parameters. The best photoperiod and feed combination for maximum growth of the cockroaches was 3L:21D and chick mash. More similar studies targeting other environmental conditions are needed to establish complete set of suitable conditions for mass rearing of cockroaches.

Keywords: Cockroach, rearing, feeding, photoperiod, growth, reproduction

Introduction
The global demand for animal protein is simultaneous with the growing human population, increasing wealth and urbanization, resulting into changes in the global consumption patterns and food preferences to animal proteins (VanHuis 2013) [25]. With a projected global population of 9.2 billion by 2050, an increase in food production by 70% is required, with meat production expected to double to meet the demand for animal protein (Vantomme *et al*. 2012) [27]. Unless food production takes sustainable approaches, these desired outcomes will not only be impossible but will add more pressure on the already constrained natural systems. Currently, feeding remains one of the biggest constraints in livestock production, making the enterprise expensive and unprofitable to many farmers in sub-Saharan Africa (Shaphan *et al*. 2019) [20]. The cost of feeds, including substitutes like fishmeal and soybean meal, represents 60–70% of the total production costs (Vantomme *et al*. 2012) [27]. Moreover, due to limited availability of low-cost feeds, livestock feeding has relegated into conventional human foods like cereals, creating livestock-human competition for food, a situation that is likely to exacerbate food insecurity. For instance, Food and Agriculture Organization (FAO) estimates a global cereal demand for animal feeding to hit one billion tons in 2050 up from 800 million recorded in 2018 (Makkar *et al*. 2018) [15]. At present, global production of conventional feed streams including protein sources like soybean, sunflower and cotton have reduced drastically due to climate change and degraded soils, and therefore sustainable innovations in livestock production including low-cost feeding and suitable micro-climates are urgently needed to improve animal production and its profitability.

Insects are novel feed resources with nutritional, environmental, and economic benefits, and can potentially improve livestock nutrition and reduce pressure on natural environments.

They have low requirements for land and water but have high feed conversion efficiency into insect biomass (Halloran *et al*. 2014) [7]. Therefore, insects as feed can significantly reduce environmental footprint of livestock production if mass-production can deliver quality proteins compared to fish or soy (Van Huis *et al*. 2015) [24]. However, their production still cannot compete with conventional feed sources despite the latter facing a myriad of production challenges (Vantomme *et al*. 2013) [26]. Notably, insect rearing industry is promising in developed and developing countries, and already a shift from semi-automated to fully automated systems is being explored as a new frontier in insect rearing in developed countries. The use of insects in livestock feeding has also gained momentum with over 70% acceptance rate reported across the world (Sagori *et al*. 2022) [22]. The common insects used in animal feeding includes black soldier fly larvae, mealworms, silkworms, cockroaches, housefly maggots, crickets, locusts, and grasshoppers. Rearing of insects such as crickets and maggots, has mostly intensified in many countries across the world including Thailand where approximately 20,000 enterprises are reported to be engaged in insect farming both for human food and livestock feed (Hanboonsong *et al*. 2013) [8]. On the contrary, other insects such as American cockroach have remained under-exploited despite their potential for use in animal feeding.

American cockroach (*Periplaneta americana*) has good nutritional value and can supply significant amount of crude protein (53.10%) in animal diet and play a similar role to conventional protein sources in animal nutrition. Like with many other insects, American cockroach holds many benefits including being climate-resilient, having high feed conversion efficiency and high reproductive capacity. Similarly, their rearing is less capital and labor intensive as they can be reared at household conditions using locally available feed resources. However, mass production and utilization of insects in animal feeding is still low in sub-Saharan communities (Ukoroije *et al*. 2020) [23]. Large-scale production is only domiciled in Asian countries such as China and Thailand where they are used to augment livestock feeding efforts. Specifically, cockroach farming for animal feeding is a new enterprise that requires strong scientific understanding of the factors and conditions that optimize production in sub-Saharan Africa to promote adoption and mass rearing.

Changes in weather and climate are known to significantly modulate insect species' dynamics, abundance, feeding and distribution (Khaliq *et al*. 2014) [11]. Environmental factors like temperature, humidity and photoperiod affect their behavior, physiology, and morphology (Karl *et al*. 2011) [10]. Consequently, these effects define insects' biotic capabilities such as longevity, development time, fecundity, and fertility. Besides, their survival and behavior are significantly influenced by availability of water, food and shelter from harsh microclimate and predators. The seasonal adaptation of some insects such as the long-range species is mediated by elevation and longitudinal transitions in temperature, seasonal length, and changes in day length (Larson *et al*. 2019) [13]. Being ectotherms, the physiological processes of insects are extremely sensitive to changes in environmental conditions and they normally change their behavior and activities in response to changes beyond their tolerance. Some of these changes includes shifting their morphology, biology, or ecology to suit the prevailing conditions and the latter affect their per capita reproductive output (Robinet *et al*. 2010) [17]. There's a critical need to understand the key factors that affect insect production such as substrates, potential allergens, environmental requirements, and their safety (Vantomme *et al*. 2012) [12]. Being nocturnal, photoperiod is one of the most important environmental factors that affect the physiology and behavior American cockroaches. However, the effect of photoperiod and its interaction effect with other abiotic factors such as feed on their growth and reproductive performance is unclear. This study aimed to bridge the knowledge gap by assessing how photoperiod and feed interact to affect American cockroach's growth and reproductive performance. This was envisaged to generate knowledge on the best photoperiodic level and feed type that optimize their growth and reproductive performance and consequently inform sensitization of farmers on the best conditions for mass production of the cockroaches for use in animal feeding. Besides, insect breeders interested in American cockroach would gain knowledge on the best photoperiod conditions and feeding behavior for genotype by environment understanding.

Materials and Methods

Establishment of cockroach colonies

Offsprings of parent colonies were used in this experiment. To establish parent colonies, two techniques were used to collect cockroaches from households around Bondo town (Kenya). One technique involved using traps made of double adhesive masking tape that were mounted in areas infested with cockroaches. The other technique involved sprinkling water on their identified habitats to expose and immobilize them for easy collection. Adult cockroaches were isolated from the trapped cockroaches to make parent colonies and were kept in specialized housing made of perforated plastic boxes measuring 30 cm by 15 cm by 25 cm kept in an area with moderate exposure to light. The parent cockroaches were fed on a composite diet consisting of chick mash and carrot mixed in the ratio of 1:1, and water provided *ad libitum* on separate 10ml capacity containers. Both carrots and chick mash have been used widely for insect feeding either independently or in their composite, and have noted to be good delicacy for insects (Rovai *et al.*, 2021) [18]. The colonies were monitored to grow and mature female individuals were separated into a third box with similar measurements to lay eggs. The eggs were collected and incubated to hatch and newly hatched cockroaches (Off springs) were raised for one month to allow them grow to more visible and easier to count before taken to laboratory for experiment. The new colony was made of male and female cockroaches that were determined by observation of the abdominal tips. Male cockroaches have a pair of a styli and a pair of cerci while the female have only a pair of cerci (Andersen, 2022) [2]. In addition, males have wings extending to about 4-8 mm beyond the abdomen tip (Barbara, 2003) [3].

Fig 1: The last nymph stage of the American cockroach

Fig 2: Adult male American cockroach showing a pair of syli and a pair of cerci at the abdomen and extended wing

Feed Preparation

Two feeds were used in the experiment to feed the experimental colonies including chick mash and, a composite of chick mash and carrot (Chick mash+ carrot). Chick mash is a blend of several feed ingredients in grounded form mostly used feed to chicks. It contains balanced diet with protein content being high. It's good for proper growth and development of the chicks. Carrot is a root tuber with almost 60% sugar, which makes it more palatable and digestible to cockroaches. Fresh carrots sun-dried and grounded into smaller granules. Chick mash and carrots were mixed in the same proportions, and mixed thoroughly to obtain a uniform mixture for use to feed the experimental cockroaches. Proximate composition of the two feeds (chick mash and chick mash + carrots) were determined before feeding to the cockroaches

Experimental design

An experimental layout to assess the effect of photoperiod and feed on growth and reproductive performance of American cockroach was designed. The experiment was factorial with two factors as photoperiod and feed. It was laid out in a split-plot design with photoperiod being the main plot factor and feed as sub-plot factor. Photoperiod was designed at four levels (3L:21D, 6L:18D, 12L:12D and 18L:6D) and feed at two levels (chick mash and chick mash+ carrot). Four cabinets were designed to represent each photoperiod level (Table 1). Each cabinet was fitted with two rearing containers for each feed type and 10 experimental cockroaches. The set-up was replicated three times with photoperiod level and feed type randomized across the three replications.

Table 1: Experimental lay out

Main plot	18L:6D		12L:12D		6L:18D		3L:21D	
Sub-plot	CM	CM+CR	CM+CR	CM	CM	CM+CR	CM	CM+CR
Main plot	6L:18D		3L:21D		12L:12D		18L:6D	
Sub-plot	CM+CR	CM	CM	CM+CR	CM+CR	CM	CM+CR	CM
Main plot	12L:12D		6L:18D		18L:6D		3L:21D	
Sub-plot	CM	CM+CR	CM+CR	CM	CM	CM+CR	CM	CM+CR

Key
CM: Chick mash
CM+CR: Chick mash+ carrot
L: D: Hours of light to hours of darkness ratio

Data collection

Proximate composition of the feeds was analyzed in triplicates and means for each nutrient taken. Measurement of body weight (g), body length and cephalic length (cm) were taken at a weekly interval. Body weight and ootheca weight were measured with electronic weighing balance, while body length, cephalic length and ootheca length were measured using a 15cm ruler with the aid of a hand lens. Hand lens were used to magnify eggs presence in an ootheca. Eggs were visible as rows inside an ootheca and appeared closely packed.

Statistical analysis

A mixed effects model was used to analyze the experimental data in a R-Studio Software version 4.1.2 and means were separated using LSD at 95% confidence level. The model used was as follows:

$$Y_{ijk} = \mu + \alpha_i + n_{k(i)} + \beta_j + (\alpha\beta)_{ij} + \epsilon_{ijk}$$

Where

Y_{ijk} – is the observed growth parameter (body weight, length, cephalic length, reproduction) of the *kth* replicate with photoperiod *i* and feed *j*.

α_i – fixed effect of photoperiod

β_j - fixed effect of feed

$(\alpha\beta)_{ij}$ – corresponding interaction term

$n_{k(i)}$ - whole-plot error

ϵ_{ijk} – split-plot error.

Results

Photoperiod on growth and reproductive performance of cockroaches

Body weight and cephalic length of the cockroaches reduced significantly with increased photoperiod levels (Table 2). Cockroaches exposed to photoperiod level 3L:21D recorded the highest significant mean body weight (0.71±0.004 g) and cephalic length (1.11±0.003 cm). Notably, the mean body weight and cephalic length were the same for cockroaches exposed to photoperiods 18L:6D and 6L:18D. The body length of the cockroaches remained statistically the same across the four photoperiods. Overall, the trend of growth in terms of body weight, body length and cephalic length of the American cockroach improved across the photoperiods throughout the six weeks of feeding (Figure 4). On the other hand, photoperiod insignificantly affected reproductive parameters of cockroaches observed in this study including ootheca length, number of eggs per ootheca and ootheca weight (Table 3).

Table 2: Mean growth performance of American cockroach across photoperiod levels

Photoperiod	Mean ± SE(g) Body weight	Mean ± SE (cm) body length	Mean ± SE (g) Cephalic length
12L:12D	0.48±0.003^{a}	2.63±0.009^{a}	0.98±0.003^{a}
18L:6D	0.59±0.003^{b}	2.83±0.009^{a}	1.05±0.003^{b}
3L:21D	0.71±0.004^{c}	2.97±0.011^{a}	1.11±0.003^{c}
6L:18D	0.57±0.003^{b}	2.80±0.010^{a}	1.04±0.003^{b}

Values are presented as Mean ± SD, n=3, where n is the number of analytical replicates for each treatment. Values in each column followed by different superscripts differ significantly (*p*≤ 0.05).

Table 3: Mean reproductive performance of American Cockroach across photoperiods

Photoperiod	Mean ± SE (cm) Ootheca length	Number of eggs per ootheca	Ootheca weight
12L:12D	1.28±0.016^{a}	11.8±0.107^{a}	0.129±0.0010^{a}
18L:6D	1.27±0.007^{a}	11.3±0.074^{a}	0.133±0.0006^{a}
3L:21D	1.31±0.009^{a}	11.9±0.103^{a}	0.135±0.0019^{a}
6L:18D	1.27±0.010^{a}	11.8±0.107^{a}	0.130±0.0018^{a}

Values are presented as Mean ± SD, n=3, where n is the number of analytical replicates for each treatment. Values in each column followed by different superscripts differ significantly (*p*≤ 0.05).

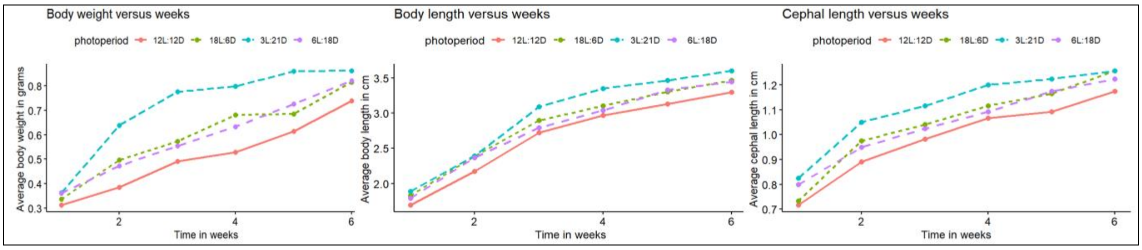

Fig 3: Trend of mean body weight, body length and cephalic length across the photoperiods and throughout the six weeks of feeding

Effect of feed on growth and reproductive performance of the cockroaches

Chick mash + carrots feed reported higher contents of dry matter, fat, crude fiber and carbohydrates compared to chick mash alone, but the latter recorded higher protein content (Table 4). Nonetheless, no significant difference was observed in the mean intake of the two feeds (p<0.000). Similarly, the two feeds insignificantly affected growth and reproductive performance of American cockroaches in this study (Table 5). Conversely, feed interaction with photoperiod reported a significant positive effect on the body weight, body length and cephalic length of American cockroach ($F_{3,278}$=1.066; p=0.0006) (Table 6). The same interaction showed insignificant effect on ootheca weight, ootheca length and number of eggs per ootheca of the American cockroaches.

Table 4: Proximate composition of feeds

Feed	Dry matter	Ash	Crude protein	Fat	Crude fiber	Carbohydrates
Chick mash	6.19±0.01	1.01±0.02	13.1±0.12	1.56±0.03	1.75±0.05	0.18±0.11
Chick mash +carrot	14.98±0.75	3.33±0.09	12.89±0.42	1.63±0.03	2.45±0.07	0.21±0.08

Values are presented as Mean ± SD, n=3, where n is the number of analytical replicates for each treatment. Values in each column followed by different superscripts differ significantly (p ≤ 0.05).

Table 5: Mean growth and reproductive parameters of American cockroach as affected feeds

Feed/parameters	Growth performance (Mean ± SE (g))			Reproductive Performance (Mean ±SE (g))		
	Body weight	Body length	Cephalic length	Length of ootheca	No. of eggs per ootheca	Ootheca weight
Chick mash	0.61±0.002^{a}	2.81±0.005^{a}	1.05±0.002^{a}	1.29±0.006^{a}	11.9± 0.055^{a}	0.131±0.0008^{a}
Chick mash + carrots	0.58±0.001^{a}	2.81±0.005^{a}	1.05±0.002^{a}	1.27±0.004^{a}	11.4±0.040^{a}	0.132±0.0007^{a}

Values are presented as Mean ± SD, n=3, where n is the number of analytical replicates for each treatment. Values in each column followed by different superscripts differ significantly (*p*≤ 0.05).

Table 6: Feed and Photoperiod interaction effect on growth of American cockroach

Source of Variation	Body weight (P-value)	Body length (P-value)	Cephalic Length (P-value)
Feed: photoperiod	0.0006*	0.0156*	0.0212*

Discussions

American cockroaches being nocturnal insects are most likely affected by the duration and intensity of light. In previous studies, it has been noted that photoperiod affect insects' behavior and physiology, and consequently their growth and reproduction (Zhu *et al*. 2004) [4]. In this study, photoperiod affected only the body weight and cephalic length of American cockroach but remained an insignificant factor in their reproductive performance. Body weight and cephalic length of the cockroaches were noted to reduce with increased photoperiodic levels. The cockroach accumulated more nutrients in their bodies as photoperiod increase from 3-12hrs while photoperiod beyond this level increased the utilization of already stored food to meet their metabolic requirements thus reducing the cockroach's body weight. There was a linear relationship between body weight of the cockroaches and the cephalic length of the insect. Cockroaches associate longer exposure to light with the long days, which symbolizes drought in the tropics for prediction of the occurrence of diapause. In fact, insects that undergo diapause must consume more food, increase their digestive efficiency and shift their nutrient use from somatic growth to storage for more reserves (Hahn *et al*. 2011) [6]. This observation is, however, inconsistent with that of, who noted fifteen times weight gain in wood cockroach when moved from dark to light phase. Although this observation can be attributed to a possible genetic difference between the two cockroaches, more insights would be gained when wood cockroach is exposed to the same conditions and its response observed.

Exposure to light is known to supply heat to some extent that is important for growth and development of both small and large organisms. Light produces photon (small packets of energy) which are transmitted in the form of electromagnetic radiations as waves as they burn especially from the light emitting diode (LED) bulbs used in the experiments. When these waves hit the surface of an organism, some portion of the radiation is absorbed by the body of the organisms thus converting short wave radiation into long wave radiations that is felt by the organism as heat (Cuker *et al*. 2019) [5]. The latter is needed for body metabolism to activate and support enzymatic and hormonal activities and to aid the formation of important body cells, organs, and other body structures. However, the right heat condition must be monitored to prevent instances of hormonal and enzymatic deactivations and inactivity that would instead slow growth and development. In this study, growth in body weight and cephalic length of the cockroaches were observed in the lowest photoperiodic level and reduced on higher levels. Apparently, photoperiodic level 3L:21D provided the best light condition that supported the metabolic activities of the cockroaches which then translated into more growth observed in the two parameters. The other photoperiodic conditions were seemingly not the best for increased metabolism resulting into reduced weight and cephalic length. Likewise, photoperiodic level was noted not to be a key factor in the reproductive performance of American cockroaches in terms of ootheca weight, ootheca length and number of eggs in an ootheca. For that reason, American cockroaches can be exposed to any of the four photoperiodic levels for the same reproductive performance. A similar observation was made by Iwasaki *et al*. (2000) [9], that noted that photoperiod do not affect early stages of insects' embryonic development. However, this observation was not specific to a particular insect but generalized to all insects and should be considered in that context. On the contrary, Shahjahan *et al*. (2020) [19], reported increased ovarian maturity for insects exposed to frequent periods of darkness. It was further noted that photoperiod effect on ovarian maturity depends on insects' physiological status and their habitat. In the present study, it was noted that reproduction of American cockroach is a predetermined stage like the case with many other organisms, where the insect body goes through adequate physiological preparation in readiness for reproduction. This preparation entails adaptations to the prevailing environmental conditions and as such, the outcome of reproductive indicators seems to be genetically defined rather than controlled by the environmental cues.

For the feed effects, the two feeds did not affect growth and reproductive characteristic of the cockroaches. Despite chick mash fortified with carrots being richer in most nutrients compared to chick mash alone this did not affect the performance of the cockroaches. Seemingly the two feeds were able to provide the needed quantities of nutrients required by the cockroaches for their growth and development. Evidently, fortification of chick mash was not an important intervention to improve performance of the cockroaches. A slight difference in the proximate composition of the two feeds was noted which would insignificantly affect cockroaches' growth when other factors are kept constant. Although not measured in this study, feed conversion efficiency which a direct indicator of feed uses and a proxy indicator of feeding, would improve understanding on how the two feeds were utilized (Smetana el al. 2021) [21]. On the flip side, photoperiod and feed interaction had a positive effect on body weight, body length and cephalic length of the cockroaches. This interaction effect can be speculated to results from the right combination of the two factors that supported the growth in body weight, body length and cephalic length. Photoperiod is reported to function as environmental cue that prompts most insects to initiate changes in behavior, development, growth, or diapause induction (Costanzo *et al*. 2015) [4].

Conclusion

Photoperiod levels 3L:21D, 6L:18D, 12L:12D, and 18L:6D did not affect body length, body weight, length of the ootheca, number of eggs per ootheca and the weight of the ootheca of the American cockroaches. Light duration of 3L:21D gave the highest mean body weight and cephalic length and thus can be considered the best photoperiodic condition for rearing the cockroaches. It is therefore advisable that farmers targeting market demand for cockroaches with a high body weight and body length to consider photoperiod level 3L:21D for rearing. However, harvesting of such stock should be done before the cockroaches reach their reproductive stage (ootheca formation) as harvesting beyond this stage reduces the weight of the cockroaches. Feeding the cockroaches with chick mash or chick mash+ carrot gives almost the same yield in terms of growth. Similarly, the two feeds were observed to provide almost same amount of nutrients for growth and development of the cockroaches, and thus farmers can consider using either feed in rearing the cockroaches with the same growth and reproductive results.

Recommendation

Further research is needed to understand how photoperiod interacts with other environmental factors other than feed to affect growth and reproductive performance of American cockroaches to enable creation of more efficient rearing/ production units. Researchers should provide more insights into the species characteristics that determine the effectiveness of the photoperiod or feed on the growth of the America cockroach for adequate weight gain and feed conversion efficiency. Further studies should be conducted to establish the reproductive stage at which feeding of the American cockroaches may not be economical in terms of reproductive viability.

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Declaration of conflict of interest
Authors of this manuscript declare no conflict of interest

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Ethical Approval
This study was ethically reviewed and approved by Jaramogi Oginga Odinga University of Science and Technology Ethics Review Committee, and the National Commission for Science, Technology and Innovation and approval granted to undertake it. The study did not involve human subjects.

Data Availability Statement
The data supporting the finding is available from the coreset landing author upon request

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