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Evaluation of a separative rearing method of the mealworm beetle for protein production

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PEKKARINEN, JOUNI: Arvio jauhopukkien erottelevasta kasvatusmetodista proteiinintuotantoa varten

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TIIVISTELMÄ

Halvan ja kestävästi tuotetun proteiinin kysyntä on jatkuvassa kasvussa Maan asukasluvun ja lisääntyvän lihansyönnin kanssa. Samalla on kasvanut huomio vaihtoehtoisia proteiininlähteitä, kuten hyönteisiä, kohtaan. Yksi lupaavimmista hyönteislajeista tähän tarkoitukseen on *Tenebrio molitor*, eli jauhopukki, ja varsinkin sen toukka, eli jauhomato.

Hyvin vähän tutkimusta on tehty liittyen hyönteisten kasvatusmetodeihin, vaikka Internetissä onkin paljon ammatti- ja harrastajakasvattajien tuottamaa tietoa. Tämän opinnäytteen tarkoituksena oli tutkia kokeellisesti, olisiko jauhomatojen tuotantoa mahdollista lisätä pitämällä täysikasvuiset kuoriaiset erossa niiden munista ja tulevasta jälkikasvusta käyttämällä apuna kasvatusastian pohjaan kiinnitettyä alumiiniverkkoa, joka siivilöi munat itsestään kuoriaisten liikkuessa ruokaseoksessa. Yksinkertaisin tapa kasvattaa jauhomatoja on pitää koko heterogeeninen populaatio (munat, toukat, kotelot ja kuoriaiset) samassa kasvatusastiassa. Hypoteesin mukaan ruokaseokseen munitut munat ja niistä kuoriutuva nuori jälkikasvu voivat helpommin vaurioitua tai kuolla, esimerkiksi kannibalismin seurauksena, mikäli niitä pidetään samassa kasvatusastiassa täysikasvuisten kuoriaisten kanssa.

Koe osoitti, että kaikkien kolmen (3) verkollisen koeryhmän jauhomatojen yhteismäärä oli noin 12 % suurempi kuin kaikissa kolmessa (3) vertailuryhmässä, joissa eli heterogeeninen populaatio (kuoriaiset, munat ja toukat). Määrä ei kuitenkaan ole tarpeeksi merkitsevä ryhmien pienen määrän vuoksi. Eri elinvaiheiden erottelulla on kuitenkin muita hyötyjä tuotannon kannalta, se nimittäin vähentää kuormittavaa ja aikaa vievää seulontaa sekä mahdollistaa paremmin elinolojen, kuten ravinnon ja ilmankosteuden, optimoinnin kasvun eri vaiheisiin.

Avainsanat: *Tenebrio molitor*, hyönteisten kasvatus, proteiinin tuotanto, hyönteisravinto, entomofagia

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ABSTRACT

The global demand for cheap and sustainable protein is ever increasing along with the Earth's population and rising meat consumption, and so is the focus on insects as an alternative source of protein. One of the most promising insect species for this use is *Tenebrio molitor*, the mealworm beetle.

Very little research has been done concerning the different rearing methods of these insects, even though the Internet is full of empiric evidence provided mostly by commercial growers and hobbyists. The aim of this study was to experiment if mealworm production could be increased by keeping the adult beetles separated from their eggs and subsequent offspring with the help of an aluminum mesh that has been attached to the bottom of the rearing container, which sieves the eggs as the beetles move around in the food mixture they inhabit. The most basic way to rear *Tenebrio molitor* is to grow the whole heterogenous population (eggs, larvae, pupae and beetles) together in the same container. The hypothesis was that the eggs, which the beetles lay directly into the food, or the subsequent offspring, can more easily get cannibalized, or harmed in some other way, if they are kept in the same container with the beetles.

The results showed that there was a small increase (~ 12%) in the amount of mealworms in the three (3) experimental groups, where the mesh was used for separation, compared to the three (3) control groups that had a mixed population of beetles, eggs and larvae. Because the total number of groups in the experiment was small, the increase is not big enough to be significant. The separation of the adult beetles has other possible benefits in production, like reducing the need for sieving and the possibility to better customize and optimize the rearing habitats, namely food sources and humidity, for the different life stages.

Key words: *Tenebrio molitor*, insect farming, protein production, edible insects, entomophagy

CONTENTS

1 Introduction

Since the beginning of the millennium, the price of food on the global market has been rising steadily and it has evoked a discussion about the ways to even further increase food production. Especially, there is a lack of cheap protein, because most of the Earth’s farmed land has been harnessed for meat production, which has considerable effects on water supply, land usage, biodiversity and climate change.

Cattle farming directly, or indirectly through the growing of feed, uses approximately 30% of the Earth’s ice-free land surface. Using such a huge portion of land for pasturing and farming modifies and diminishes natural environments. Livestock and manure release many gasses, such as methane and nitrous oxide, which contribute to climate change. In many cases nutrients, pathogens and drug residues found in rivers, lakes and seas originate from livestock farming. Because of the obvious limitations in the amount of farmable lands, alternatives are in great demand. (FAO 2006.)

During the last decade, numerous news sites, organizations and scientific magazines have showed interest in entomophagy, or the consumption of insects as food. This is no wonder, since many insect species are known to be at least as good as traditional livestock in terms of nutrition. Various insects are eaten by the majority of humans, intentionally and unintentionally, as many processed products contain small amounts of insect bits and pieces. The average protein content of dried insects is 40 - 75%, most of which (77 - 98%) is easily absorbable and composed of essential amino acids (Verkerk, Tramper, Van Trjip, & Martens 2007).

One advantage of insect farming over traditional livestock is lower emissions of greenhouse gases, even though energy use is still higher compared to milk and chicken production and is similar to the requirements of pork and beef production (Oonincx 2010). Insects also tend to have a faster life cycle, more efficient conversion of feed to biomass and a considerably smaller need for space (Oonincx, 2012). For example a mealworm, the larva of the mealworm beetle, *Tenebrio Molitor*, can convert 53 – 73% of its feed to biomass. The conversion factors are 38 – 43% for chicken and 10 – 12% for cows (Ramos-Elorduy 2008; Wilkinson 2011).

The aim of this thesis is to study if it is possible to increase mealworm production with a farming method which separates the breeding mealworm beetles from the rest of the population. An aluminum mesh will be used in an experiment to separate the mealworm beetles and their eggs into different containers. The number of mealworms produced in these test groups will be compared to the amount produced by the control groups, in which the mealworm beetles are allowed to live in the same substrate with their eggs and subsequently hatching larvae.

The hypothesis is that the beetles might, intentionally or not, eat or harm their offspring and reduce the amount of potential mealworms. This experiment was inspired by news articles about the prospects of insect protein and by positive observations posted by mealworm breeders about the benefits of separating the different life stages on Youtube (e.g. “My Mealworm farm – With Filter” video by username eve2831). The separation also allows differences in feed and humidity conditions between the adult beetle population and the rest.

A system in which eggs are separated from beetles and hatched in separate chambers will help alleviate the danger of losing the larvae population due to microbial infection such as fungus, because the adult beetles, which thrive in high moisture conditions, can be kept in a separate environment without exposing the rest of the population to excess moisture and increased infection risk (Ghaly & Alkoaik 2009).

2 Background

My interest in insects as a protein source was probably first sparked by news stories and articles about entomophagy, i.e. the consumption of insects as food. The topic has emerged a couple of times during the last few years, as can be observed, for example, from news pieces like “Insects could be the key to meeting food needs of growing global population” by Damian Carrington and “Insects will be important part of UK diet by 2020, says scientist” by Rebecca Smithers in The Guardian (1 August 2010, 31 March 2011), “Edible insects produce smaller quantities of greenhouse gasses than cattle” in Science Daily (9 Jan 2011), “Waiter, there’s soup in my bug” by Jeff Gordinier in The New York Times (21 September 2010), and “UN urges people to eat insects to fight world hunger” in BBC (13 May 2013).

Inspired by the news, I read the 2006 UN report Livestock’s long shadow, which deepened my interest in local and global food production and led me to study alternative ways of protein production. This includes the direct usage of insects as human food, but also the many possibilities different species might provide as animal feed.

Insects are one of the most diverse classes of invertebrates, which represent the vast majority of animal species, so there is a broad range of species to choose from. There are species that probably will not be beneficial, or they might be nearly impossible to rear, but chances are that there are more than a few that could be harnessed for some use. Some of the desired characteristics are fast reproduction, high feed to protein conversion rate, high quality protein, low greenhouse gas emissions, low land and energy use, and the possibility to utilize biowastes or other organic side streams, such as manure, as feed for the insects. Many insects could outperform conventional livestock in these traits, and it would lead to direct cost reductions that can be used to gain an advantage in the market.

Mealworms have often been the subject of news stories and most of the research that I found, and maybe not without a reason, as they seem to possess most of the aforementioned good traits. This is what made me want to look deeper into mealworm production, and to the ways it could be improved.

2.1 The life cycle of *Tenebrio molitor*

The mealworm beetle, *Tenebrio molitor*, belongs to a family of darkling beetles; Tenebrionidae (Table 1). Its life cycle consists of four stages of growth: egg, larva, pupa and adult beetle (Figure 1).

TABLE 1: Taxonomy of the mealworm beetle (The National Center for Biotechnology Information 2013)

Kingdom:	**Animalia**
Phylum:	Arthropoda
Class:	Insecta
Order:	Coleoptera
Family:	Tenebrionidae
Genus:	***Tenebrio***
Species:	***T. molitor***

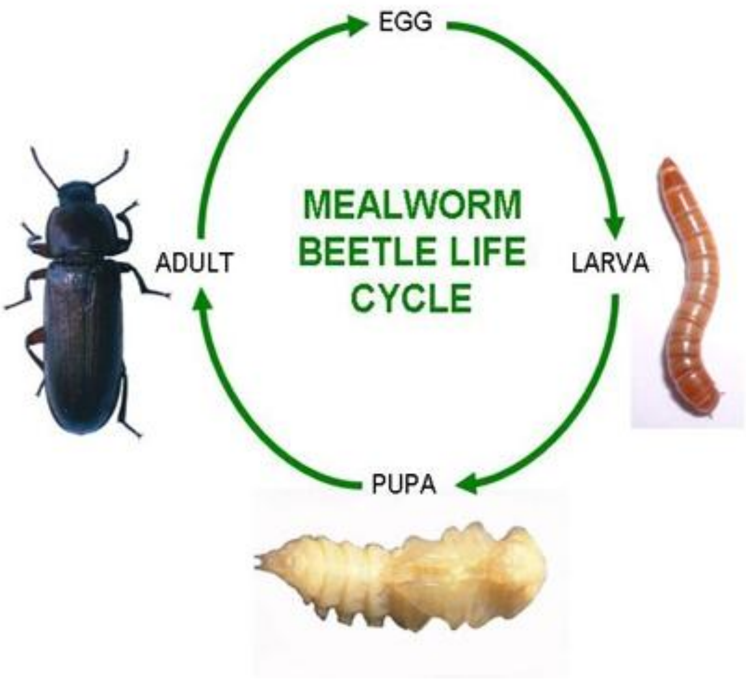

FIGURE 1: Life cycle of the mealworm beetle (New York Worms 2013)

2.1.1 Mealworm beetle and egg

The average adult beetles range from 1.25 to 1.8 cm in length and are black or dark coloured. At first they are white, but they start turning darker and reach sexual maturity in a couple of weeks after emerging from pupae, after which they start to mate and lay eggs in clusters into the substrate/food medium they live in. The female deposits an average of 400-500 eggs that are bean shaped, sticky and white. The eggs are 1.7-1.8 mm in length and 0.6-0.7 mm in width. The time of incubation is affected by temperature, the optimum being 2 weeks at 25 °C (Ghaly & Alkoaik 2009).

2.1.2 Larva

The tiny larvae, known as mealworms, are white and almost invisible to the naked eye once they hatch. Fully grown larvae are approximately 2.5-3 cm long and about 3 mm thick with a yellowish, segmented and relatively hard skin, which they molt 9-20 times before losing the carapace and turning into pupal form (The University of Arizona 1997).

TABLE 2: Amino acid content of mealworm larvae (g / 100 g) (Ghaly & Alkoaik 2009)

Alanine 6.8
Arginine 4.3
Cysteine 5.6
Glycine 2.0
Glutamic 12.3
Histidine 1.7*
Isoleucine 4.8*
Leucine 8.2*
Lysine 5.3*
Methionine 2.0*
Phenylalanine 4.6*
Serine 4.7
Threonine 4.0*
Tryptophan 0.7*
Tyrosine 4.0
Valine 6.4*

***Essential amino acids**

A mealworm contains all of the essential amino acids and their ratio to total amino acids is 44.7%. The ratio has been reported to be higher than that of pork, lamb or beans, and to almost equal beef and fish. (Li et al. 2012).

2.1.3 Pupa

The pupae are about 1 cm long, mostly immobile, with colour ranging from white to yellow as they mature. The length of this life stage is heavily influenced by temperature, as it ranges from 6 days at 28 °C to 18 days at 18 °C (A.E. Ghaly & F.N. Alkoaik, 2009). The emerging beetles are white, but soon the colour starts to change towards dark brown. They stay motionless unless touched or harassed in some other way, after which they wiggle aggressively for a while. Most likely this is a safety mechanism against predators or hostile environments.

2.1.4 Habitats and diet

These mostly nocturnal beetles and larvae are found worldwide and in the wild they eat decaying leaves, sticks, grasses and occasionally new plant growth (The University of Arizona, 1997). They are considered to be a minor pest of grain products; the beetle prefers rotting and damp ground grains, but it will also devour flour, brans, bread, meat scraps, vegetables, feathers and other insects. They can be found in dark and damp places, like under rotten wood or inside logs, grain silos, feed sacks, chicken litter, mills, production facilities, storages, birds' nests and also human dwellings. (Australian Wildlife, 2013)

Mealworms can adapt to tolerate a wide range of temperatures, as they act and eat normally at 15–40 °C, and can survive at 0–15 °C and 40–45 °C (L. Li, et al., 2012).

2.2 Commercial use of mealworms

Mealworms are considered to be a good source of protein and they are commercially utilized as baits and feed for many species of fish, birds, reptiles and mammals. They are grown all over the world in a variety of different scales and methods. This can be observed by reading online forums (e.g. reptileforums.co.uk, herppi.net), where hobbyists who grow mealworms discuss different rearing methods, or through introduction videos of insect rearing companies (Al-Jazeera 2011).

There are many companies that produce and sell mealworms, along with other insect species. Mealworms are mostly sold to zoos, pet shops (as feeder insects for insectivores) and baitshops, but some of them even go for human consumption. Mealworm products targeted for human consumers range from small bags of fried and spiced up mealworms to pure insect flour, which can be added into other products in order to increase protein content.

According to a cradle-to-farm-gate life cycle analysis by Oonincx & de Boer (2012), which was done through collaboration with a commercial mealworm producer (van de Ven Insectenkwekerij, Deurne) in The Netherlands, the energy usage of mealworm production is higher compared to milk and chicken production and is similar to the requirements of pork and beef production (Figure 3), but it produces much less greenhouse gases (Figure 2) and requires much less land than chickens, pigs or cattle (Figure 4). The relatively high energy use is due to climate control that is needed for optimal growth in poikilothermic mealworms.

Also, because mealworms are invertebrates, no meat by-products or slaughterhouse wastes are being produced, so the percentage of usable protein (per animal) is higher than in livestock.

There is probably a lot of room for improvement in the mealworm production chain, because even the productivity of chickens and pigs has increased annually by 2.3% over the last two decades, even though they have been farmed for ages. If the volume of mealworm production can be dramatically increased and the price of insect protein decreased, they might become economically feasible to sell as protein feed for farmed fish, poultry or pigs. (Oonincx & de Boer 2012)

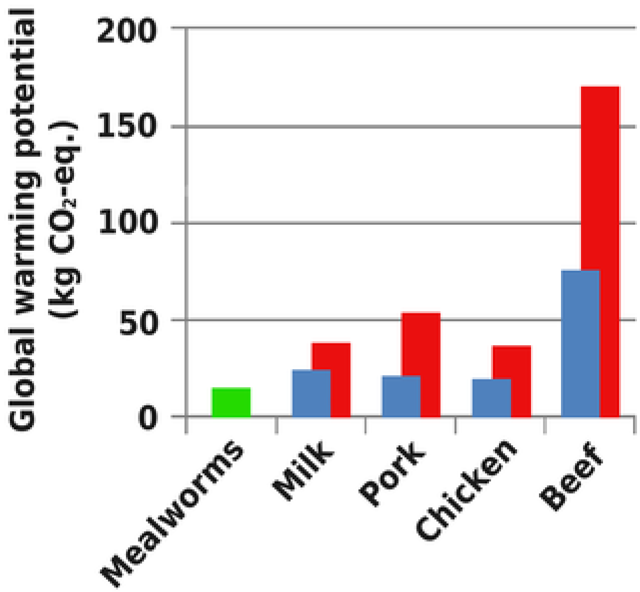

FIGURE 2: Global warming potential of mealworms compared to other animal products. The minimum values are in blue and the maximums are in red. (Oonincx & de Boer 2012)

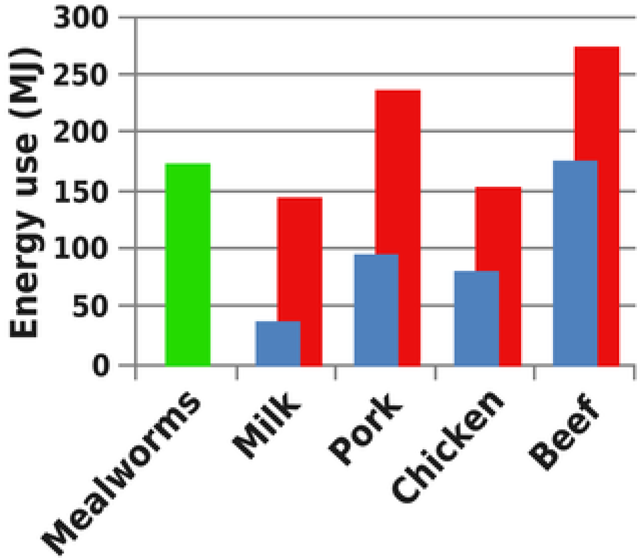

FIGURE 3: Energy use required for the production of one kg of edible protein. The minimum values are in blue and the maximums are in red. (Oonincx & de Boer 2012)

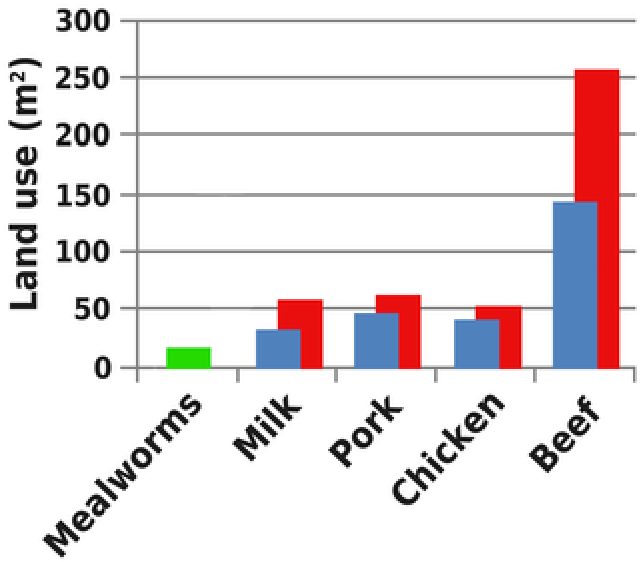

FIGURE 4: Land use resulting from the production of one kg of edible protein. The minimum values are in blue and the maximums are in red. (Oonincx & de Boer 2012)

2.2.1 Problems of large scale rearing

When producing mealworms without complex automatisation, most of the work like feeding, moving and separating the different stages of life, is done by hand. Even though some big producers exist, they all seem to use relatively shallow stacked containers that are being moved around with carts. None of the life stages of the mealworm beetle can climb smooth and vertical surfaces that most plastic containers have, so the use of shallow containers gets the job well done by allowing more of them to be stacked on top of each other.

To increase production, the efficiency must be increased so that the amount of manual work gets minimized. Because of the large number of needed containers, most of the manual labour in mealworm farming involves moving them, or a part of their content, in some way. This can be laborious if the containers are kept stacked, because it means that they have to be assembled and disassembled into towers repeatedly when doing maintenance work or harvesting.

2.2.2 Separating different life stages

The separation of larvae, pupae, beetles and eggs might be one way of maximizing production, since it has been observed by hobbyists that mealworms tend to grow in greater numbers when the beetles are separated form the rest of the population. Apparently the adult larvae and beetles can sometimes harm the small larvae, pupae and eggs, or they might be more exposed to microbial infection in a more crowded or moist environment. As the population gets bigger, more moisture is needed in the form of vegetables, for example. If the portions get too big for the mealworm population to handle in time, the moisture might take too long to absorb and the conditions can get favourable for microbes (Ghaly & Alkoaik 2009). Young offspring and pupae could also die accidentally, as the immobile and fragile pupae are not able to defend themselves very well and the tiny eggs stick to the feed and might accidentally get eaten.

In order to do the separation effectively, the different life stages should be separated as early as possible. The most logical solution is to have a separate population of breeding beetles and to sieve their substrate, which is full of eggs, from time to time. This results in fairly uniform larvae populations growing in the substrate. The age variation inside a larvae population in this kind of setup is then determined by the time between sifting. This kind of setup seems to be in use in at least one mealworm breeding company (van de Ven Insectenkwekerij, Deurne, The Netherlands), which becomes apparent when looking at a figure depicting their mealworm production system (Figure 5) in the LCA by Oonincx & De Boer (2012), even though it sheds no light on the exact procedures . The second option, which is experimented with in this study, is to add a tightly looped mesh to the growing container, under the population, and let the motion of the insects sieve the eggs into another container. This approach also has the possibility of creating all-larvae populations that are fairly uniform in size and age, by changing the bottom container at desired intervals. The uniformity in size is very important when growing commercially, especially for the pet industry, since mealworms are often sold in batches of a certain size. The all-larvae populations of same age will eventually turn into beetle only populations, which can be used as breeding populations without additional need for sieving.

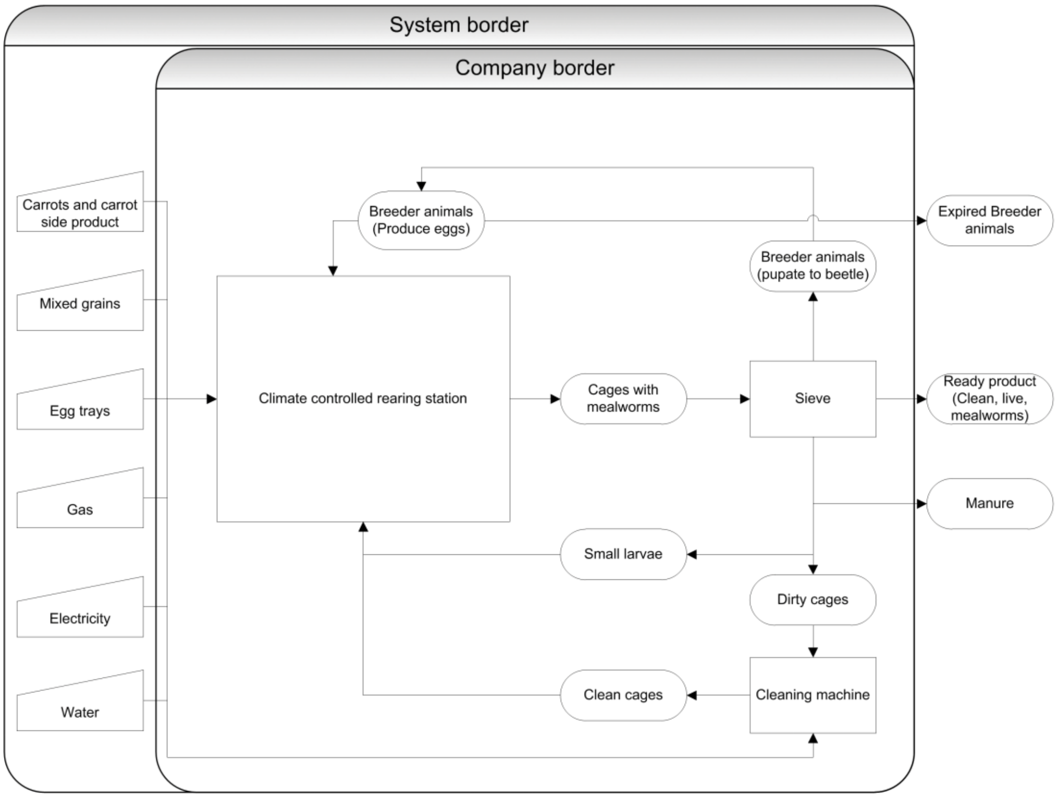

FIGURE 5: The mealworm production system (Oonincx & De Boer 2012)

2.2.3 Harvesting

For maximal protein production, the larvae should be harvested at a weight of 100-110 mg. After reaching this weight, the growth starts to slow down and after a while reverse as they prepare to transform into a pupa (Ghaly & Alkoaik 2009). If the population is heterogenous, efficient harvesting will require the separation of harvest-ready worms from the rest of the population, which can be time consuming if done manually with a sieve.

Harvesting from a uniformly aged and sized population is easy, as the only thing to do is to separate the larvae from the food mixture/substrate that is devoid of any valuable eggs. Even if there are some eggs left in the sieved substrate, they can be added back to the cycle with the feed.

3 Materials and methods

3.1 Mealworm beetles and larvae

Initially 1000 grams of live mealworms were bought and shipped from an internet pet store (petshop.fi). The mealworms were then raised on oatmeal, full grain flakes of rye, wheat, barley oat and different fresh vegetables, such as slices of carrots, apples, cucumbers and potatoes. They lived in a large plastic container that was kept in room temperature and out of direct light.

After a few weeks, the first pupae started to appear and they were picked up with a spoon and transferred into a separate container. Beetles that emerged in the pupae container were the ones used in the experiment.

3.2 Containers

The containers used were clear polypropylene containers that hold 3100 ml. The beetles cannot climb smooth plastic surfaces, neither do they fly, so the containers were fairly shallow (11 cm) and the bottom was square (16 x 16 cm).

PICTURE 2: A modified container before stacking

PICTURE 3: A modified container

There were a total of six rearing containers, three of which had been modified so that the plastic from the bottom was cut off and it was replaced with an aluminum mesh (Pictures 2, 3) small enough to keep beetles from falling through. The mesh was secured in place with cable ties, one in each corner. Three additional containers sat under the modified containers. The modified containers were built for the test groups to test the hypothesis.

3.3 Growing medium, conditions and food sources

The growing medium, which also served as the main food source, was a mix of Guldsol full grain flakes (rye, wheat, oat and barley) and Rainbow dry yeast. Dry yeast was added because it is a good source of B vitamins and folic acid, both of which are needed for sustained growth (Fraenkel 1950).

Apart from adding cucumber and inspecting the containers for dead beetles, the containers were kept in total darkness inside a relatively large rectangular compartment (56.5 x 59 cm) with minimal air flow in high room temperature (24-

26 °C) and relative humidity below 30%. Fresh air was provided with a daily maintenance check.

3.4 Preparation and maintenance

Before the experiment started, a 3 cm layer of full grain flakes was added into the six containers in equal portions, after which a bag of dry yeast (11 g) was mixed into the flakes of every container. The mixture lasted through the whole experiment and was not added to, even though the level got considerably lower in the upper containers of the test groups.

A maintenance check was done nearly every day, during which temperature, moisture level and signs of dead beetles, new larvae, mold and pests were looked for. Each time a dead beetle was noticed, it was switched with a random live beetle from the stock population.

Raw and fresh cucumber was added into the containers in equal portions a few days after the previously added vegetable matter had been consumed or dried up. This was done to prevent the grain mixture from getting too moist, which could lead to problems with mold and grain mites. I have noticed that mealworms can survive for long periods (weeks, even months) in relatively low humidity (below 30%) without a direct water source, so this feeding frequency was considered to provide them with as much water as they would need.

Adding cucumber to the lower part of the modified containers was started only after first signs of tiny white mealworms could be seen through the bottom of the containers. This was also done to avoid problems with excess moisture, as there were no beetles in the lower containers of the experimental groups that could draw the water from the slices of cucumber, or from the moistened grain mixture, before the first mealworms emerged. For the same reason, a small piece of cardboard was put under the slices of cucumber in the beetle containers before the first larvae emerged (Picture 4). After the first larvae had hatched, cucumber was also added in small slices directly on the grain mixture for easier access.

PICTURE 4: A modified container after adding the beetles

3.5 The rearing experiment

The experiment lasted from November 11, 2012 (day 0) to January 15, 2013 (day 66). On day 0 ten (10) dark coloured and lively mealworm beetles were chosen and transferred into each three control (3) and test (3) groups with a spoon on the first day of the experiment. These traits were chosen because they are indicators of healthy and mature beetles. This was especially important because the sex of the beetles was not confirmed. The experiment would stop once I estimated that there were enough, but not too many, mealworms for one person to manually count without too much error.

The experiment was done in order to determine whether separating the beetles from the rest of the population (eggs and larvae in this case) would lead to an increase in the amount of surviving offspring. The hypothesis was that the beetles might, intentionally or not, consume, trample, infect or harm their offspring in some other way, leading to a reduction in the amount of potential adult mealworms in the control groups.

4 Results

On day 66 (January 15, 2013), every visible mealworm in all six containers was counted. This included both white and yellowing mealworms. The counting was done by carefully going through the entire contents of the containers, during which mealworms were transferred with a teaspoon into a black plastic container with a compartment for every container (Picture 5).

After the control and test groups were separated from the growing medium (grains, frass, dry yeast and beetles) and transferred into the compartments, the number of mealworms in each was counted, one by one, as they were transferred into a glass bowl with a teaspoon.

PICTURE 5: A plastic container with compartments for easy separation of groups

TABLE 3: The number of mealworms in each control and test group after the experiment (day 66)

Container	Mealworms/container
Control Group 1	250
Control Group 2	336
Control Group 3	269
Total (controls)	**855**
Test Group 1	385
Test Group 2	342
Test Group 3	230
Total (test)	**957**

The total number of mealworms, and the number in two out of three containers, in the test groups was slightly higher than in the control groups (Table 3). There were a total of one hundred and two (102), or approximately 12% (957 / 855 - 1 = 11,929…), more mealworms in the test groups. The medians of control (269) and the test groups (342) groups differed by 73 mealworms, or approximately 27% (342 / 269 - 1 = 0,271…). It was also observed by eye, without any valid measuring, that the mealworms in the experimental groups were a bit larger in general, but this was only the case in two out of three test groups compared to the controls.

On March 31, 2013, 75 days after the experiment, the containers and growing medium used in the study were inspected again for signs of mealworms that might have been accidentally left unnoticed while counting. This was done in order to get an idea of the margin of error. Surprisingly, there were a couple of adult mealworms alive that had grown into full adult size without extra water, because they obviously had escaped the scrutiny. However, the total amount of leftover mealworms (< 5 / container) was insignificant compared to the total amount in each container, so the initial counting by hand was fairly accurate in a situation that had a huge potential for human error. Mealworms are not easy to detect, as they burrow to avoid light, blend into their substrate quite nicely and can stay motionless for long periods.

5 Discussion

The use of a fairly small amount of experimental groups (6), and beetles (10) in each container, was chosen to make counting easier and more error free during and after the experiment. With a large amount of evading and burrowing beetles, the daily counting during maintenance checks would have been impossible without digging and harassing the population for hours each day. But there is a downside to the accuracy; the variation in the number of mealworms is so small that it is hard to make any solid conclusions from the results, other than that the separation of the beetles from their eggs causes no reduction in the number of mealworms in the population. Even the variation between every individual group was surprisingly small, considering the fact that the sex of the beetles was not confirmed at the start of the experiment. Still, the beetle populations got some random variation when dead beetles were replaced with live ones during maintenance checks.

The number of beetles may have had an effect on the results in favor of the control groups, because as the amount of beetles increases, so does the alleged chance for the eggs to get eaten, trampled or to die due to microbial infection. However, a larger number of beetles would have sieved the substrate material faster and therefore separate the eggs more efficiently.

As mentioned in the preparation section of materials and methods (page 10), cucumber was only added into the lower containers in all test groups when the first signs of tiny mealworms could be seen. This may have had a negative impact on the amount of mealworms that survived until they could be counted, as the smallest mealworms might be more susceptible to low moisture due to their size and underdeveloped skin.

The diet of the mealworms was apparently sufficient, as there were not that many dead mealworms at the end of the experiment, even though the beetles had to be replaced from time to time. However, the death of the beetles was more likely due to their mixed age than poor diet. A more restricted diet could have provided more insight about the prevalence of cannibalism between the different life stages of *Tenebrio molitor*. Also, analyzing the nutritional content of the eggs, and the nutritional needs of the adult beetles and mealworms, might give a clue about the nutritional supplements that could be added in order to prevent the possible cannibalism for nutrients.

If the containers had been sealed (with small holes for air), the experimental groups might have had an advantage, as the humidity would have been higher due to a higher amount of fresh vegetable mass. At least one big mealworm producer, which provides many universities and zoos with mealworms, states that: "Beetles lay more eggs when the relative humidity is higher - ideally 70% (55-80% is good)" (Exotic Nutrition 2009). However, the containers had no lid and they were kept in a relatively large rectangular cabinet (56.5 x 59 cm), where the extra humidity could easily disperse into the surroundings or into the growing medium. In either case, the possible advantage, gained from the leaking moisture reaching the beetles in the upper container, was most likely insignificant and short lasting. No sudden increases in relative humidity were noticed in the cabinet after adding cucumber for moisture, which indicates that the amounts simply were not enough to cause significant rises of humidity in that space.

A second type of test groups could have been included in the experiment, which would have been similar to the control groups in composition, but with increased or reduced surface areas. This could have been interesting, since the test groups already had double surface area compared to the control groups, even though it was not available for the whole population. The speculated test groups could have been used to show whether the claimed increase in surviving offspring was just a result of increased surface area. The aim of the speculated second test groups, to study the effects of crowding on the reproduction of *Tenebrio molitor*, could very well be its own topic of research.

Conclusions

The difference between the control and the test groups was insignificant and not enough to indicate that keeping the beetles separated from the eggs and larva might lead to an increase in the yield of mealworms. Because keeping the life stages apart causes no apparent harm either, the information might still benefit the commercial mealworm producer, since separating the beetles and the eggs minimizes the need for sifting later on, reducing the amount of manual labour involved, and makes it easier to grow and harvest mealworms of similar size and age. Automatization, which probably is in its infancy in large scale insect farming, could be used to aid in sifting. Even with efficient sifters, it would be more efficient to sift eggs from an adult beetle population than to sift larvae from a population of mixed life stages, because the required amount of sifting would be minimized. In order to sift mature and harvest ready mealworms out of a mixed population would require weekly sifting because of the age differences.

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