D3.1 Characterisation /description of biological, technical and economic requirements for monitoring and decision support in insect rearing process

corosect.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101016953

Author(s)/Organisation(s)	LUKE, CIHEAM, OAMK
Contributor(s)	Miika Tapio, Maija Karhapää, Sabina Avosani, Maria Luisa Vitale, Vincenzo Verrastro Susanne Heiska, Manne Hannula, Jarkko Niemi, with consultations from TECNOVA, NASEKOMO, ENTOMOTECH, ENTOCYCLE, ICF, INVERTAPRO
Work Package	WP3
Delivery Date (DoA)	M18
Actual Delivery Date	30/6/2022
Abstract:	Most agricultural production systems have some level of automation to reduce the labor input in routine activities. However, in insect farming, substantial amount of labor input is still required for tasks such as feeding, collection, cleaning and rehousing. This limits the use of insects in food and feed value chains, raises production costs and reduces demand for and the production volumes of insect products. This deliverable reviews biological, technical, and economic aspects of processes to achieve biologically desirable or acceptable conditions at the different steps of the production process, while accounting for acceptable variations in production results. It also reviews the key parameters, which could be monitored by sensors and parameters which must be taken into account in task 3.3 when developing model-based decision support system for *Hermetia illucens* (black soldier fly, BSF), *Tenebrio molitor* (mealworm) and *Acheta domesticus*. BSF and mealworms are monitored mainly at container or population level rather than individual level. House crickets are also monitored at population level, but individuals are more visible especially at the later stages of development. Rearing conditions vary by insect’s development stage and some stages have unique biological needs. Hence, diverse sensing approaches suitable for both dry and wet conditions are needed to assess production performance. For BSF, important parameters to be monitored include temperature, humidity, air pressure, (bio)chemical and gases to maintain a benign environment, and substrate condition. Substrate quality such as nutritional content and pH can also provide valuable information. Key performance indicators for house cricket include parameters such as growth, feed conversion ratio and mortality. It is essential to have information also on the nutritional content of feed and to increase the size and automation level of the facility. Ambient conditions such as temperature, L:D cycle, humidity, and rearing density space influence the insect development. Rearing conditions should allow the insects to sustain continuous generations of offspring. In mealworms, high larval density may cause pupation inhibition, cannibalism, incomplete development and lower growth rates. Mealworms are more flexibile to relative humidity than temperature. Controlling L:D cycle and oxygen concentration is also important for a successful rearing outcome. Mealworm may display high variability in developmental time, which increases the challenges of controlling the biological process.

Document Revision History			
Date	**Version**	**Author/Contributor/ Reviewer**	**Summary of main changes**
11/11/2021	0.1	Miika Tapio, Maija Karhapää, Sabina Avosani, Maria Luisa Vitale, Vincenzo Verrastro Susanne Heiska, Manne Hannula, Jarkko Niemi	First drafts of chapters
13/6/2022	1.0	Miika Tapio, Susanne Heiska, Maija Karhapää, Manne Hannula, Jarkko Niemi	First full draft
22/6/2022	1.1	Sabina Avosani	Review and revision
27/6/2022	1.2	Jarkko Niemi	Revision based on the review
30/6/2022	1.3	Vincenzo Verrastro and Juan Cortés Ortiz	Review
30/6/2022	2.0	Jarkko Niemi	Final version

Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the EC Services)	
RE	Restricted to a group specified by the consortium (including the EC Services)	
CO	Confidential, only for members of the consortium (including the EC)	

Funding Scheme: Innovation Action (IA) ● Topic: H2020-ICT-46-2020

Start date of project: 01 January, 2021 ● Duration: 36 months

CoRoSect Consortium			
Participant Number	Participant organisation name	Short name	Country
1	UNIVERSITEIT MAASTRICHT https://www.maastrichtuniversity.nl/	UM	NL
2	ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS https://www.certh.gr/	CERTH	GR
3	HOCHSCHULE EMDEN/LEER https://www.hs-emden-leer.de/en/	HSEL	GER
4	LUONNONVARAKESKUS https://www.luke.fi/	LUKE	FIN
5	OULUN AMMATTIKORKEAKOULU OY - OULU UNIVERSITY OF APPLIED SCIENCES https://www.oamk.fi/fi/	OAMK	FIN
6	FUNDACION PARA LAS TECNOLOGIAS AUXILIARES DE LA AGRICULTURA http://www.fundaciontecnova.com/	TECNOVA	ES
7	KATHOLIEKE UNIVERSITEIT LEUVEN https://www.kuleuven.be/kuleuven/	KU LEUVEN	BEL
8	ATOS IT SOLUTIONS AND SERVICES IBERIA SL https://atos.net/en/	ATOS	ES
9	ROBOTNIK AUTOMATION SLL http://www.robotnik.es/	ROB	ES
10	AGVR BV www.agvegroup.com	AGVR	NL
11	NASEKOMO AD https://nasekomo.life/	NASEKOMO	BG
12	ENTOMOTECH SL http://entomotech.es/	ENTOMOTECH	ES
13	ENTOCYCLE LTD https://www.entocycle.com/	ENTOCYCLE	GB
14	SOCIETA AGRICOLA ITALIAN CRICKET FARM SRL https://www.italiancricketfarm.com/	ICF	IT
15	INVERTAPRO AS https://www.invertapro.com/	INVERTAPRO	NOR
16	FIELD LAB ROBOTICS BV https://www.fieldlabrobotics.com/	FLR	NL
17	FoodScale Hub https://foodscalehub.com/	FSH	RS
18	AgriFood Lithuania DIH https://www.agrifood.lt/	AFL	LT
19	CENTRO INTERNAZIONALE DI ALTISTUDI AGRONOMICI MEDITERRANEI http://www.iamb.it/	CIHEAM	IT

Table of Contents

List of tables

List of figures

List of Abbreviations and Acronyms	
AC	Automation case
BSF	Black soldier fly
DSS	Decision support system
IMS	Information Management System
L:D	Light:Dark
MDSS	Model-driven Support System
MES	Manufacturing Execution System
PIF	Precision Insect Farming

1 Introduction and approach

1.1 Background and objectives of the study

Due to the continuous growth of the world population, which is expected to reach 9.3 billion people by 2050, the demand for food and protein sources for feed is increasing. Insects are the largest group of living organisms on the Earth (Stork, 2018) and are used as human food in several parts of the world (Jongema, 2017). Edible insects could both resolve human health issues such as malnutrition and food insecurity and be a solution to the environmental degradation due to agro-industrial production (Wade and Hoelle, 2019). The use of insects as for food and animal feed is gaining a growing interest, and several production projects operating at an industrial scale already exist.

The advantages of rearing insects are many: they grow and reproduce quickly and have a high feed conversion efficiency. From hundreds of thousands existing insect species, only a few have really been farmed for food or feed (for example, black soldier fly larvae (Diptera), common housefly larvae (Diptera), silkworms (Lepidoptera), termites (Isoptera), grasshoppers (Orthoptera), locusts (Orthoptera) and yellow mealworm larvae (Coleoptera)) under large scales (Jongema, 2017). In addition to produce food or feed, insects have been used in other bioconversion processes.

Most livestock and agricultural production systems have some level of automation to reduce the expense of labor input in routine activities. However, in insect farming, substantial amount of labor input is still required to complete tasks such as feeding, collection, cleaning, and rehousing (Rumpold and Schluter, 2013). This limits the use of insects in food and feed value chains. In order to transform insects to an attractive alternative source of feed and food, automation and robotization must be further developed to reduce labor intensity and decrease the production costs, and hence end products' prices, and to ensure the availability of sufficient volumes of insect products. In addition to the labor costs, the rearing conditions such as temperature, light (stray or unintended light), photoperiod, humidity, ventilation, stray sounds, vibrations or odors, rearing containers, population density, oviposition sites, feed and water availability, feeding behavior, feed composition and quality, inbreeding and microbial contaminants must be controlled at levels which enable successful (mass) production of insects (Clifford *et al.*, 1977, Cohen 2018, Rumpold and Schluter 2013).

A digital representation (a digital twin) of the farming process can help to design and improve the rearing process as a whole. Data-driven analytic approaches and modelling based on existing data can be utilized to optimize farming processes and technology. Moreover, using artificial intelligence and deep data mining can enhance yield and sustainability (Chia *et al.*, 2018). In this perspective, autonomous robotics, centralized distribution systems, process standardization and interaction of farming techniques enable reliable, stabile, and low-cost insect production. Insect handling systems like automated feeding, (de)stacking, (un)loading, sorting, and tipping technologies are used in efficient insect production systems (Lai *et al.*, 2020, Wang and Zhu 2020).

Measuring tools, sensor technology and internet-of-things can be used to monitor the rearing environment and performances of the insect farm in real-time (Sandeepa and Thavarajah 2021, Vajpayee and Yogi 2021). Since insects develop and grow rapidly and they may be sensitive to changes in rearing conditions, it is essential to make necessary adjustments in the rearing process based on the monitored parameters. In order to control the process successfully, it is essential to identify the key parameters to be monitored, the desirable range of parameters' values and their contribution to the outcome of the rearing process.

The smart rearing system can facilitate hatching, feeding, monitoring the growth and emergence of insect larvae and pupae (Jansen *et al.*, 2019, Massaro *et al.*, 2018). An integrated camera system with a neural network for example can assist in assessing the constitution of worms by using the segments of the larvae for evaluation (Kröncke *et al.*, 2020). However, different rearing environments may require different sensing solutions. For example, insects living and growing in a moist substrate likely require different monitoring methods than insects living on the surface of dry substrate.

The CoRoSect decision support system (DSS) will be part of the Information Management System (IMS) and Manufacturing Execution System (MES), which will be used to connect, monitor, and control the overall manufacturing process and data flows within the insect farm. The CoRoSect system will consider four interlinked automation cases, which comprise: (i) transport of the crates containing the insects; (ii) detection and measurement of the rearing conditions; (iii) management of the rearing processes; (iv) insect handling and processing.

The overall aim of CoRoSect WP3 is to gain understanding on biological, technical, and economic requirements of insect rearing processes and improve them through management, sensing, and automation. The aims are (i) to identify and describe factors that are critical for a successful and sustainable insect rearing process; (ii) to identify, test and facilitate the use of printed sensors in monitoring insect rearing processes; (iii) to develop sustainable insect diets for mealworm, crickets, and black soldier flies; (iv) to present a model-driven support system for optimizing insect rearing.

This deliverable focuses on characterizing biological, technical, and economic aspects of the subprocesses to achieve biologically desirable or acceptable conditions at the different steps of the production process, while accounting for biologically and economically acceptable variations in production results. The deliverable reviews the key parameters, which could be monitored by sensors, their desirable range of values, and the significance of automating the rearing process, and summarized data needed to develop a digital representation of insect farming processes. The reported work is closely related to tasks 2.1, 2.2, and 3.3, and D2.2 of the CoRoSect project. As opposed to end-user derived data of D2.2, D3.1 is mainly based on information extracted from the scientific literature and it aims at generalizable information on insect rearing. In addition, D3.1 supports tasks 3.2 and 3.3. As three insect species *Hermetia illucens* (black soldier fly, BSF), *Tenebrio molitor* (mealworm) and *Acheta domesticus* (house cricket) will be considered in the CoRoSect project, the following chapters will consider requirements for all these species.

1.2 Summary of methods applied for this deliverable

The rearing processes of *H. illucens* (black soldier fly), *T. molitor* (mealworm) and *A. Domesticus* (house cricket) were first described by using expert knowledge of the authors and other partners involved in the CoRoSect H2020 project. This knowledge was complemented with information that was available in published rearing guides and other relevant literature (such as Caruso *et al.*, 2013; Dortmans *et al.*, 2017; Joly and Nikiema, 2019). Moreover, end-user derived knowledge among CoRoSect partners was utilized, and this information (with flow charts) was described in deliverable 2.2. These consultations were done together with CoRoSect WP2 during year 2021.

Sensor technologies can be used to monitor and control the insect rearing process. For these purposes, it was identified what parameters need to be monitored and what parameters should be controlled. In order to summarize information concerning rearing process and ambient condition parameters, as well as the desirable range of parameter values, scientific literature concerning the rearing of each three insect species was briefly reviewed and summarized. Studies for the review were searched by using search engines (Google, Web of science). While being a wide review, this was not a systematic review. The key words in the search included the names of insect species, and key words describing biology, rearing, farming, survival, growth and rearing conditions of insects.

The titles and abstracts of studies identified by the search were screened and studies which appeared to provide relevant information were selected for more detailed reading. Finally, qualitative, and quantitative information on the relevant rearing process parameters were extracted from the studies. These data are summarized in the results tables of this deliverable.

We also identified in what steps sensors can provide the most useful information regarding the processes. The potential of sensors to support the monitoring and control of the biology of insect rearing process was summarized by combining research team's expertise on available sensors and their potential applicability in rearing process.

In order to characterize economic significance of the outcome of insect rearing, the costs items of insect rearing each insect species were identified. Then, the sensitivity of rearing process outcome to changes in biological parameters was examined as a desk work in order to characterize how sensitive the process was to failures in the insect rearing process. To identify the sensitivity of costs to parameter alterations, the most important performance parameters of rearing were varied according to the range of variation of identified by the literature review.

1.3 References

Caruso D., Devic E., Subamia W.I., Talamond P. and Baras E. (ed.) 2013. Technical handbook of domestication and production of Diptera Black Soldier Fly (BSF) *Hermetia illucens*, Stratiomyidae. PT Penerbit IPB Press, Kampus IPB Taman Kencana Bogor. 159 s. ISBN: 978-979-493-610-8.

Chia S.Y., Tanga C.M., Khamis F.M., Mohamed S.A., Salifu D., Sevgan S., *et al.*, 2018. Threshold temperatures and thermal requirements of black soldier fly *Hermetia illucens*: Implications for mass production. PLoS ONE 13(11): e0206097. https://doi.org/10.1371/journal.pone.0206097.

Clifford W., Roe R.M. and Woodring J.P. 1977. Rearing methods for obtaining house crickets Acbetu domesticus of known age, sex and instar. Annals of the Entomological Society of America 70 (l), 69– 74.

Cohen A. 2018. Ecology of Insect Rearing Systems: A Mini-Review of Insect Rearing Papers from 1906-2017. Advances in Entomology, 6, 86-115. doi: 10.4236/ae.2018.62008.

Dortmans B., Diener S., Verstappen B.M., Zurbrügg C. 2017. Black soldier fly biowaste processing - a step-by-step guide. Dübendorf, Switzerland: Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Jansen J., Hendrikus A., Schol B. and F. Jürgens 2019. Insect Breeding Device. Available online: https://patentimages.storage.googleapis.com/f8/33/0c/b5072cba2cb2a2/WO2019125165A1.pdf

Jongema, Y., 2017. List of edible insect species of the world. Laboratory of Entomology, Wageningen University, Wageningen, The Netherlands.

Joly G., and Nikiema J. 2019. Global experiences on waste processing with black soldier fly (*Hermetia illucens*): from technology to business. Colombo, Sri Lanka: International Water Management Institute(IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 62p. (Resource Recovery andReuse Series 16) doi: 10.5337/2019.214.

Kröncke N., Baur A., Böschen V., Demtroder S., Benning R., Delgado A. 2020. Automation of Insect Mass Rearing and Processing Technologies of Mealworms (*Tenebrio molitor*). In book: African Edible Insects As Alternative Source of Food, Oil, Protein and Bioactive Components. DOI: 10.1007/978-3-030-32952-5_8. (only abstract).

Lai D., Gu D., Huang X., Su K. 2020. Breeding device and breeding system. Available online: https://patents.google.com/patent/CN111328772A/en.

Massaro P., Sobecki R., Behling C., Criswell V., Zha T., Devengenzo R. 2018. Automated mass rearing system for insect larvae. Available online: https://patentimages.storage.googleapis.com/7e/f2/59/068769b27a3482/WO2018067376A1.pdf.

Rumpold B.A. and Schluter O.K. 2013. Potential and challenges of insects as an innovative source for food and feed production. Innovative Food Science and Emerging Technologies 17: 1–11.

Sandeepa N. and Thavarajah P. 2021. IOT For Agriculture. Available online: https://www.researchgate.net/publication/350213463_IOT_For_Agriculture.

Stork, N.E., 2018. How many species of insects and other terrestrial arthropods are there on Earth? Annu. Rev. Entomol. 63, 31–45.

Vajpayee P. and K.K. Yogi 2021. Recognition and Early Stage Detection of Phytophthora in a Crop Farm Using IoT. DOI: 10.5772/intechopen.97767. Available online: https://api.intechopen.com/chapter/pdf-preview/77361.

Wade, M., Hoelle, J., 2019. A review of edible insect industrialization: Scales of production and implications for sustainability. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/aba1c1

Wang X. and Zhu K.C.H. 2020. Automatic black soldier fly breeding and unloading system. Available online: https://patents.google.com/patent/CN111149777A/en.

2 Black soldier fly (*Hermetia illucens*)

2.1 Bio-physical information on the rearing process

2.1.1 Basic information

The black soldier fly (*H. illucens*, order Diptera, family Stratiomyidae) is currently one of the most used insect species to produce biomass for food and feed in the industrialized countries. In wild, it feeds on dead and decomposing organic material and is found globally in temperate and tropical regions (Sheppard *et al.*, 1994). The widespread distribution and the ease of maintaining in a colony (Sheppard *et al.*, 2002) has contributed to the global interest in its mass production as protein source (Tomberlin *et al.*, 2015).

The farming of BSF is transitioning from small-scale towards larger, industrial scale production. Transforming the most labor-intensive work phases into an industrial scale and automated process is essential for supplying large volumes of BSF products at competitive prices to the markets. Thanks to emerging technology development and published BSF breeding guides (Caruso *et al.*, 2013; Dortmans *et al.*, 2017; Joly and Nikiema, 2019), the basic biological and technological knowledge has become more widely available to the practitioners. However, the full potential of BSF has not yet been exploited.

2.1.2 Life cycle

Hermetia illucens is less than 3 cm long and has a wasp-like appearance as an adult. During this stage is blue or black, while the color varies from pale beige to black among the other stages. During the development, black soldier fly experiences a complete metamorphosis with five main stages, each characterized by a duration: egg (4 days), larva (18 days), prepupa and pupa (14 days), and adult (9 days) (Sheppard *et al.*, 2002, Figure 1). The life cycle in optimal conditions is only about 45 days in total (Barragán-Fonseca *et al.*, 2017). *Hermetia illucens* spends the larval stage in the growing media (substrate) and moves away from dryer areas when transforming from prepupa to pupa, eventually leaving the substrate when transforming from pupa to an adult (Diener, 2010; Joly and Nikiema, 2019).

This species lives in groups of several thousands of adults or larvae grow in dense colonies, which can reach population density up to 14kg/m^2. The adaptation to diverse environments and nutrient sources and the natural development in large groups make the species well suited to mass rearing. The larvae can reduce the feedstock weight by 50–80% and convert up to 20% (on a total solid basis) into larval biomass within 14 days (Diener *et al.*, 2011a; Lalander *et al.*, 2015, Zhou *et al.*, 2013). However, the diverse environments required for the live stages and larvae living submerged in a substrate comprises a challenge for monitoring progress and survival and for controlling or optimizing each rearing step.

While adult maturation, mating behavior and oviposition can be visually monitored and the adult stage of BSF rearing occurs in open air, the main stage influencing the production outcome (i.e., the larval stage), occurs in a wet matrix and in darkness, which hampers the monitoring options. Indirect sensing methods are therefore needed. When monitoring larvae, four observations per hour are needed. Alarm thresholds for deleterious extreme conditions should be set and ammonium gas levels should be monitored closely to enhance both human and animal wellbeing. Monitoring the larvae is mainly based on ambient or growth substrate monitoring, while in the adult stages monitoring is more focused on ambient environment or on the use of remote sensing solutions. However, the production systems' details vary and influence the monitoring options, and in practice, only a subset of potentially important factors can be monitored. Crate groups might be mixed at the mating stage and sometimes in egg or neonate stage, making detailed group ancestry documentation challenging.

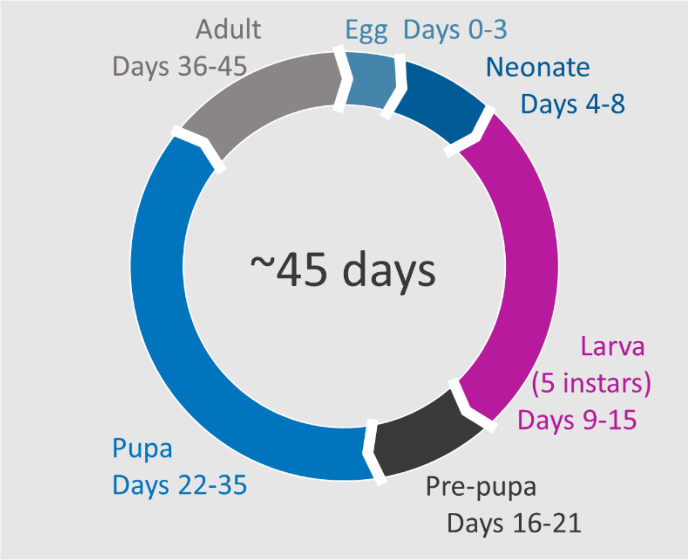


Figure 1. Approximate life cycle of black soldier fly.

2.1.3 Key performance parameters of BSF

Currently, the rearing of BSF in Europe is mostly carried out in small scale and with little automation. Increasing the scale of farming to a level where this species could make a substantial contribution to the volume food production requires that automation and the control of rearing process is improved, as this will influence the competitiveness. In practice, this requires automating both the labor-intensive parts of the process and process monitoring and developing decision support tools which facilitate data-driven control of the rearing process. For this, it is essential to identify what needs to be monitored, how and under what range the parameter values are expected to occur. During the life cycle of BSF, several parameters are measured to assess the performance of the rearing process (Table 1, Figure 2).

2.2 Sensing approaches to monitor the rearing process

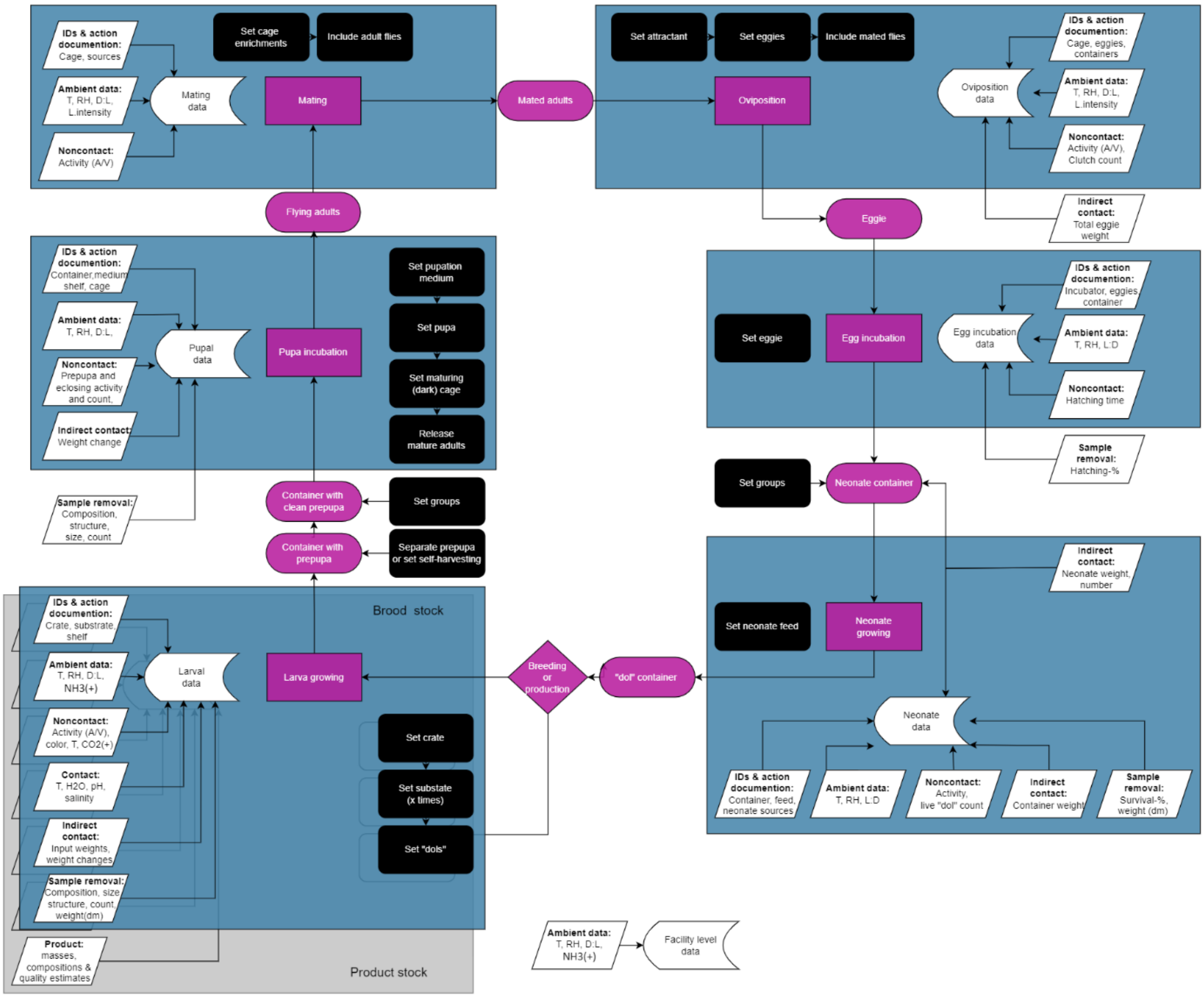
Precision livestock farming is a tool for active livestock management with a focus on enhancing the economic, social, and environmental sustainability of farming. In addition to animal identification, physiological measurements which can be made by sensors include feed and water intake, movements, individual weight, body temperature, respiration rate, sweating rate, immunosensors, and heart rate variability. Some of these parameters are relevant also for BSF, and they can be measured by different types of invasive and non-invasive sensors. BSF are generally followed at container or population level rather than individual level. (Table 2). However, *H. illucens* fly stages have biological unique needs, thus diverse sensing approaches are needed to evaluate their performances.

Table 1. Life-history traits and performance (mean value ± standard deviation, SD) of black soldier fly fed either chicken feed or diets of similar crude protein and fat contents as chicken feed.

Life-history or performance trait[1]	n[2]	Mean±SD	References
Egg stage (days)	3	2.7±0.6	Gobbi (2012)
Larval developmental time (days)	12	24.2±2.7	Diener *et al.* (2009b, 2011b), Gobbi (2012), Nguyen *et al.* (2013), Oonincx *et al.* (2015a), Tomberlin *et al.* (2002)
Prepupa and pupa developmental time (days)	3	15.8±6.9	Nguyen *et al.* (2013)
Pupal developmental time (days)	3	7.1±1.1	Gobbi (2012)
Total cycle (days)	7	42.6±5.1	Gobbi (2012), Nguyen *et al.* (2013), Tomberlin *et al.* (2002)
Larval survival rate (%)	8	86.2±10.0	Gobbi (2012), Nguyen *et al.* (2013), Oonincx *et al.* (2015a), Tomberlin *et al.* (2002)
Prepupal survival rate (%)	1	93.0±2.9	Lalander *et al.* (2018)
Pupal survival rate (%)	6	88.0±15.6	Gobbi (2012), Nguyen *et al.* (2013)
Larval weight (g FM)	3	0.204±0.046	Diener *et al.* (2011b), Nguyen *et al.* (2013) Tomberlin *et al.* (2002)
Larval length (mm)	1	20.5	Nguyen *et al.* (2013)
Larval DM content (%)	1	33.9±2.28	Oonincx *et al.* (2015a)
Prepupal weight (g FM)	4	0.176±0.07	Diener *et al.* (2009b), Gougbedji *et al.* (2021), Lalander *et al.* (2018), Tomberlin *et al.* (2002)
Prepupal weight (g DM)	5	0.058±0.02	Diener *et al.* (2009b, 2011b), Gougbedji *et al.* (2021)
Prepupal DM content (%)	3	37.1±1.9	Diener *et al.* (2009b), Gougbedji *et al.* (2021), Spranghers *et al.* (2017)
Pupal weight (g FM)	6	0.145±0.005	Gobbi (2012)
Adult weight (g FM)	1	0.059±0.008	Tomberlin *et al.* (2002)
Adult weight, male (g FM)	1	0.053±0.007	Tomberlin *et al.* (2002)
Adult weight female (g FM)	1	0.064±0.006	Tomberlin *et al.* (2002)
Adult weight (g DM)	1	0.024±0.007	Diener *et al.* (2009b)
Adult length (mm)	2	15.8±0.14	Gobbi (2012)
Adult length male (mm)	1	15.7±0.24	Gobbi (2012)
Adult length female (mm)	1	15.9±0.21	Gobbi (2012)
Adult longevity, with water (days)	1	8.9±0.57	Tomberlin *et al.* (2002)
Adult longevity, without water (days)	1	6.8±0.49	Tomberlin *et al.* (2002)
Adult mortality rate (%)	3	24.4±?	Nguyen *et al.* (2013)
ECI DM (%)	1	23.0±5.3	Oonincx *et al.* (2015a)
N-ECI	1	52.0±12.2	Oonincx *et al.* (2015a)
ECD FM (%)	1	29.5±5.9	Diener *et al.* (2009b)
FCR	1	1.8±0.7	Oonincx *et al.* (2015a)
Dry weight reduction of feed (%)	3	35.1±8.0	Diener *et al.* (2011b)
WRI	1	2.34±1.15	Diener *et al.* (2009b)
Biomass conversion ratio (% DM)	1	12.8±0.7	Lalander *et al.* (2018)

[1] DM = dry matter, ECD = efficiency of conversion of digested food, ECI = efficiency of conversion of ingested food, FCR = feed conversion ratio, defined as feed intake /average daily gain, WRI, Waste reduction index, defined as substate consumption/feeding time, FM = fresh matter.

[2] Number of independent experiments.



T=temperature, RH=relative humidity, H2O=moisture, D:L=Dark:light cycle, L. = light, A=audio, V=visual, CO2=carbon dioxide, NH3= ammonia (might be measured as dissolved ammonium), dm=dry mass

Figure 2. A simplified flow chart sketching time-stamped sensing and tracking data that can be used for quality assurance and improvement in the biological black soldier fly larvae production process. Technical flow chart is presented in Figure 9 of D2.2.

Sensor-based data about the location and proximity of insects can be used to control and monitor resources and actions. Temperature, humidity, air pressure, (bio)chemical and gases can be used to maintain a benign environment and substrate condition, to observe environmental deviations that are compromising a successful production process as well as to forecast the progress of insect rearing as a process. Machine vision and other imaging technologies can be used to monitor a range of different features such as hatching and oviposition performance as female activity, the number, activity and condition of neonate larvae, prepupae, pupae and adults, egg mortality and the condition of substrate. Motion that can be measured by monitoring the batch (e.g. crate) can provide information on activity and the status of insect population, whereas changes in the weight of the batch and the substrate can provide indications on the growth of insects and their mortality.

Table 2. Potential indicators to be monitored by sensors to inform about the farming process status by the stage of farming cycle and by approach to measure indicators, and indicators of successful rearing outcome of each rearing stage of black soldier fly.

Sensing approach	Egg	Neonate	Larva	Prepupa and pupa	Maturing adult	Breeding adult
ID and location of animal	Eggie, Eggie container Attractant container	Neonate container Feed batch	Crate Substrate batch	Pupa container Matrix batch	Dark cage Adult batch	Breeding cage Breeding batch
Ambient conditions	Temperature Humidity (RH) Light cycle	Temperature Humidity (RH)	Temperature Humidity (RH) Light intensity Gases*	Temperature Humidity (RH)	Temperature Humidity (RH)	Temperature Humidity (RH) Light intensity Loudness
Contact (in crate)			Substrate temperature, moisture, pH, salinity and nutrient composition**	Temperature Moisture		
Noncontact	Clutch count Hatching	Larval count and activity	Larval count, activity, and color distribution Substrate surface color, structure and temperature Crate gases* and humidity	Prepupal count and activity Surface gases (CO2, O2) and humidity		Breeding status Activity
Upon sample removal	Moisture Hatching proportion	Survival	Moisture pH Salinity Composition	Moisture	Enclosing proportion Average weigh	
Indirect contact	Eggie weight (pre/post)	Average weight				
Indicators of rearing success	Number of eggs and neonates	Survival rate of neonates, number of larva	Biomass growth of larva, survival rate of larva	Biomass growth of pupa, number of adults released	Number of mated flies	Amount of oviposition

* CO_2, NH_3, CH_4, O_2, **Approximate nutrient composition of substrate is to be known in advance.

2.2.2 Egg stage

BSF egg production takes place in controlled-environment breeding cage or similar space ranging from one cubic meter to tens of cubic meters, with open air and landing areas that host from thousands to hundreds of thousands of adult flies. The rearing facility of egg stage needs to be maintained under stable conditions, thus approximately 27°C, 60–70% relative humidity, and 14:10 L:D light cycle (Tomberlin *et al.*, 2009). A female lays a single clutch of eggs (320–900) two days after mating (Booth and Sheppard 1984; Tomberlin and Sheppard, 2002; Tomberlin *et al.*, 2002; Sheppard *et al.*, 1994). The egg is approximately 1 mm in length and creamy white in colour (Diclaro and Kaufman 2009). Egging racks, or eggies, are placed near decomposing grain saturated with water (substrate) or other rotting organic matter. Decaying food scrap will attract female to lay their eggs (Ortiz *et al.*, 2016; Yang 2017). Egging equipment can be a weighed cardboard blocks (2–3 cm thick, 3–5 cm long, 2–3 cm wide) or reusable stacks of wood with small crevices. Females will oviposit in the cracks, typically filling a small number of neighboring holes, and the quantity of eggs oviposited by females can be estimated by counting the number of filled holes and measuring the increased total weight. While egg hatching takes about four days in optimal conditions (Booth and Sheppard, 1984; Tomberlin *et al.*, 2002), low temperatures can significantly impact hatch time and viability (Holmes 2010).

The focus in the egg stage is in monitoring the environment to ensure favorable ambient conditions for the egg development. Relative humidity of 25% is known to cause high rates of desiccation and mortality (Holmes *et al.*, 2012) and would be observed also as fewer neonates per egg mass. Recording both environment and the efficiency of egg production and hatching rate can reveal problems such as calibration errors or harmful contaminations or lowering vitality of the breeding stock which require closer attention. The collected eggs can be partitioned into two groups, first one to maintain the colony and the second for mass production.

Batch and equipment IDs and tending activity are useful additional information for following the performance egg production. If the breeding cage is emptied periodically, it is possible to identify the parent batches and therefore keep traceable record over the lifecycle of the batch. The approximate ovipositing time and egg number can be recorded when all egging equipment are changed periodically. Many eggs of an egg clutch typically hatch approximately at the same time and this might be detected visually as movement and visual change in the egg plug of in the crack.

2.2.3 Larva stage

Eggies are placed and incubated in small containers. When hatching occurs, the larvae fall in the container, and a small amount of a standard diet, such as the Gainesville diet (Hogsette, 1992), at 70% moisture, is provided to the neonate larvae for the first 5–7 days (2–3 first instars). The small larvae might be counted and subdivided to known sized groups either before or after the first feeding and growing period. This can be based on either direct counts or determining average weight based on subsamples and using the neonate mass weight as a proxy for the larval count. As counting and subdividing larvae can be time consuming, automation with for example artificial intelligence-based counting methods can be used in BSF production. The neonates are sensitive to variation in temperature. For example, Tomberlin *et al.* (2009) reported 74–97% survival at 27 and 30°C but only 0.1% at 36°C.

Under controlled conditions (Gainesville diet, at 28°C, 75% RH, photoperiod of 16:8 (L:D) h), BSF larval development lasts 18–25 days and they grow from 3 mm to about 20 mm (Zhou *et al.*, 2013). The larvae begin as light cream turning to light brown in later with a small black head (Sheppard *et al.*, 2002). When larvae are continuously fed and the growing aims to produce mature pupa, feeding can be terminated when approximately 40% of the larvae are black, which indicates they have entered the prepupal stage and do not ingest feed anymore (Tomberlin *et al.*, 2002).

Rearing conditions influence the development time of BSF. In extreme case, the development time may increase up to four months (Furman *et al.*, 1959; Tomberlin *et al.*, 2002, 2009; Holmes 2010; Myers *et al.*, 2008). Temperature is usually closely followed and adjusted, because even small temperature differences may influence development time. For example, Tomberlin *et al.* (2009) reported larvae at 27°C to take 4.1 days longer to complete larval and pupal development than those at 30°C (33.6 vs. 37.7 days). The impact of the substrate is more complex to predict and analyse compared to temperature. The larvae consume from 25 to 500 mg organic matter per individual per day depending on their size, the type of the substrate available and environmental conditions (e.g., moisture content of the feedstock, temperature, and air supply) (Makkar *et al.*, 2014).

Indicative target features are presented in Table 3. The basic nutriment requirements (vitamins, minerals, amino acids) and potential anti-nutritional compounds present in substrates remain inadequately known (Caruso *et al.*, 2013). Interestingly, within certain limits substrate moisture can be more important than one of the most basic nutritional traits, the ratio between protein and carbohydrate content (Cammack and Tomberlin, 2017). Even if larvae are photophobic (Zhang, 2010), *H. illucens* reared in complete darkness develop slower than those reared in the presence of light (8 h or 12 h per day, at 27°C) (Holmes *et al.*, 2017).

Monitoring the ambient environment at room or incubator level is crucial when larvae are fragile neonates. At later stages, the ambient environment has less direct impact, as the larvae are embedded in moist substrate. Gregarious species with high metabolic activity and high-density production systems produce significant levels of carbon dioxide and heat (Slone and Gruner, 2007; Hansen *et al.*, 2006). In addition to insect heat production, microorganisms present in the rearing media also produce heat and gasses. As some substrates may be more easily consumed by larvae after bacterial or fungal decomposition (Dortmans *et al.*, 2017) certain microbial processes can be applied as a substrate pre-treatment (Yu *et al.*, 2011). Heat and gas production of both insects and microorganisms should be estimated and considered in the system design and monitoring (Ortiz *et al.*, 2016). In addition to the ambient environment, this heat generation and mechanical mixing by the larvae influence also the substrate drying. Larvae stage is the most variable and ready for optimization and the monitoring data can be used not only ensuring normal benign conditions, but also predicting the development. The larvae stage has the clearest needs for crate-specific monitoring.

Table 3. The desirable range of parameter values for black soldier fly rearing.

Parameters	Range of favourable rearing conditions	Parameters	References
Density	Larva: 1.2…5 larvae/ cm^2 1…2.5 larvae/g (substrate) Adults: 6500 ind./m^3		Parra Paz *et al.* (2015), Pastor *et al.* (2015), Gobbi *et al.* (2013), Hoc *et al.* (2019)
Light intensity (µmol/m2 /s) λ 450–700 nm	Adults: 135–200	Adults: >60	Alvarez (2012), Holmes (2010), Tomberlin and Sheppard (2002), Zhang *et al.* (2010)
Humidity (%RH)	60…70	Adults: 25…99	Joly and Nikiema (2019), Tomberlin and Sheppard (2002), Gobbi (2012), Holmes *et al.* (2012)
Temperature (°C)	27…31	15…36	Chia *et al.* (2018), Sheppard *et al.* (2002), Tomberlin *et al.* (2009) Booth and Sheppard (1984), Holmes (2010), Holmes *et al.* (2016), Sheppard *et al.* (1994), Tomberlin *et al.* (2009), Holmes *et al.* (2012)
Substate			
Feeding rate (dry base)	95…163 mg/larva/day		Parra Paz *et al.* (2015), Diener *et al.* (2009a)
Moisture content (%)	52…70	40…90, avoid free water	Cammack and Tomberlin (2017), Cheng *et al.* (2017), Dortmans *et al.* (2017), Lohri *et al.* (2017), Sheppard *et al.* (2002), Tomberlin *et al.* (2009), Fatchurochim *et al.* (1989), Furman *et al.* (1959), Tomberlin *et al.* (2002)
pH	6.5…8	4…9	Caruso *et al.* (2013), Dortmans (2015), Lalander *et al.* (2015), Rehman *et al.* (2017a, 2017b)
Salinity (%)	< 1	<4	Cho *et al.* (2020), Kwon and Kim (2016)
Particle size	<2 cm	Not established	Dortmans *et al.* (2017), Lohri *et al.* (2017)
Structure	Sufficient structure to allow the larvae to move through the feedstock, consume it and breathe		Barry (2004), Perednia (2016)
Nutrient content	Feedstock rich in protein and carbohydrates (e.g., 21% protein and 21% carbohydrate); Suitable C/N ratio: 10–40 (optimal nutrient balance not established). High contents of volatile solids are preferable	Not established	St-Hilaire *et al.* (2007a), Gobbi *et al.* (2013), Lalander *et al.* (2015), Cammack and Tomberlin (2017), Dortmans *et al.* (2017), Lohri *et al.* (2017), Rehman *et al.* (2017a, 2017b), Lalander *et al.* (2018)
Fiber content	Not established	Not too high	Zheng *et al.* (2012a), Caruso *et al.* (2013), Lohri *et al.* (2017), Mohd-Noor *et al.* (2017), Rehman *et al.* (2017a)

2.2.4 Prepupa and pupa stage

The stage between larva and pupa stage is the "prepupa" stage (7 days) wherein they cease to eat and empty their guts, while their mouth parts change to an appendage that aids climbing (Sheppard *et al.*, 1994). Under laboratory conditions, the larvae reach this stage in two weeks at 30 °C (Furman *et al.*, 1959). Pre-pupae (black, 15–20 mm) crawl out of the moist feed source to search for a humid sheltered area to pupate. By using a specially designed bioreactor, the typical migrating behavior of prepupae can be exploited, allowing self-harvesting of prepupae (Sheppard *et al.*, 1994). They are often a bit larger than the mature pupae stage (Newton *et al.*, 2005; Georgescu *et al.*, 2020).

The pupation stage of BSF lasts about two weeks or longer depending on the substrate (Tomberlin *et al.*, 2002) and the environmental conditions (Tomberlin *et al.*, 2009; Holmes 2010). The exoskeleton darkens in pigmentation and a pupa develops inside of the exoskeleton (Kaleka *et al.*, 2019). No specific material is necessary for pupation. Holmes *et al.* (2012) demonstrated that *H. illucens* reared at 70% RH with no pupation substrate has 93% emergence success. However, the use of pupation material is recommended as it can protect the pupa from desiccation (Holmes *et al.*, 2013). While the prepupa tolerates cool temperatures (16–18 °C), the advanced pupa is more sensitive to cold. When using cool to slow development, the environmental data might have a predictive value, but otherwise the sensing is done more to maintain benign optimal conditions and to follow moisture.

2.2.5 Adult stage

Adults (flies) emerge after 10–14 d after pupation at 27–30°C (Sheppard *et al.*, 2002). Males typically emerge first, whilst females follow about 2 days later (Tomberlin *et al.*, 2002). The flies (length 15–20 mm) have a life span of 5 to 14 days (Tomberlin *et al.*, 2002; Ussery 2009). Adults live solely to mate and lay eggs (Sheppard *et al.*, 2002), thus they do not have full functioning digestive track for eating, though they can drink. Adults rely on fat body as energy reserves, which were stored during the larval stages. These reserves are visible also to other flies through the abdominal “window” and influence adult fitness and longevity (Liu *et al.*, 2008; Tomberlin *et al.*, 2002). Even if adults do not feed, their longevity is increased when provided with a source of water (Tomberlin *et al.*, 2002; Caruso *et al.*, 2013), and simple dissolved carbohydrates (Rachmawati *et al.*, 2010; Nakamura *et al.*, 2016).

Adult flies typically mate and oviposit at temperatures from 24 °C to 40 °C, even if in the field 99.6% of oviposition occur between 27.5 and 37.5 °C (Booth and Sheppard, 1984). According to Chia *et al.* (2018), fecundity is significantly affected by temperature, especially at temperature below 15˚C and above (37˚C) survival thresholds. The highest fecundity of *H. illucens* was observed at 30˚C (Chia *et al.*, 2018). Temperatures below 27°C result in reduced adult activity, and consequent lower matingpairs and oviposition rates (Tomberlin and Sheppard, 2002). Adult life span and pupal development time decrease when temperature is higher than the optimal range of 26–27 ˚C (Barragán-Fonseca *et al.*, 2017; Shumo *et al.*, 2019). High humidity is also associated with longevity, as adult *H. illucens* live 2–3 d longer at 70% RH than at lower (25 and 40%) RH levels (Holmes *et al.*, 2012).

The adult lekking behavior is critical for mating (Tomberlin and Sheppard, 2001). In this regard, adults are known to form aggregation sites where males attempt to secure a female in flight and mate with her. As consequence, colonies are to be maintained in cages to promote mating (Dortmans *et al.*, 2017; Yang 2017). Adults typically mate for two days after emergence (Tomberlin and Sheppard 2002). Mating can be achieved if a BSF male intercepts a passing female in mid-air, and if they descend in copula (Tomberlin and Sheppard, 2001). The mating environment is the most demanding to create and suboptimal temperature, moisture, light intensity, and L:D cycle and deviations from the optimal conditions is quickly observed in behavior and success rates, which together with the environmental characteristics require close monitoring.

2.3 Monitoring product quality and risk assessment

The substrate or equipment contamination during the farming could increase microbial risks, because BSF are farmed in moist warm environment in microbe-rich medium. Though black soldier fly larvae are less affected by infection to several potentially pathogenic bacteria such as *Salmonella spp.* (Erickson *et al.*, 2004; Lalander *et al.*, 2013) and *Escherichia coli* compared to other farmed species (Erickson *et al.*, 2004; Liu *et al.*, 2008; Vogel *et al.*, 2018), pathogen monitoring and hygienic treatments are recommended. In addition to microbes (Boccazzi *et al.*, 2017), unwanted pest insects need to be controlled (Reguzzi *et al.*, 2021). These might be detected as deviations from derived performance, but generally automatic detection with precise diagnostics is challenging.

Chemical contamination might impact product quality or safety. There are reports indicating that heavy metals might accumulate in the exoskeleton of prepupae (Diener *et al.*, 2015; Bulak *et al.*, 2018). Regarding toxic feed contaminants, Diener (2010) found cadmium, lead, and zinc in BSF prepupae fed on organic waste. None of the three heavy metals had significant effects on life cycle traits (prepupal weight, development time, sex ratio) nor on the bilateral symmetry of the adult flies. However, cadmium accumulated in the prepupae and could thereby potentially limit its use in the production of animal feed. Diener (2010) also concluded that neither lead nor zinc accumulate in larvae or prepupae, which means concerns about the use of prepupae in animal feed might be less critical. Nonetheless, when proteins and lipids are extracted, heavy metals may be discarded as they remain in the chitinous exoskeleton. These contaminants have low concentrations and have insignificant impact on BSF performance, and therefore may need to be analyzed separately.

The main by-product in the BSF production is frass. Frass is mixture of insect faeces, substrate residues, and shed exoskeletons (Cadinu *et al.*, 2020). It is an inevitable side-stream during the mass-rearing of insects that can add up to 75% of the fed substrate (Diener *et al.*, 2009b) and is often merchandised as a fertilizing product (Schmitt and de Vries 2020). Many studies have focused on meaningful applications of insect frass (Choi *et al.*, 2009; Alattar *et al.*, 2016; Vickerson *et al.*, 2017; Sarpong *et al.*, 2019; Quilliam *et al.*, 2020; Klammsteiner *et al.*, 2020a). Field studies have provided promising perspectives for its application in agriculture, especially in terms of plant nutrient availability (Beesigamukama *et al.*, 2020a, 2020b, 2020c). The substrate used to grow insects affects the properties of the frass, since undegradable residues remain unused, while the digested fraction is modified by the gut microbiota when passing through the gastrointestinal tract (Klammsteiner *et al.*, 2020b).

2.4 Benefits of measurement technology and data

The principles of the development stages of the BSF and the main features of optimal breeding conditions are well known. However, the literature review clearly shows that there may be variations in growing conditions, and it is evident all details related to breeding are not yet unequivocally known. Better management of these conditions and their variation through measurement technology may bring great benefits for optimizing the partially or wholly automated production of BSF.

The measurement technology makes it possible to gain greater awareness of the state of the production process currently underway. In such a case of use, the basic purpose of the measurement is to ensure conditions about the main factors such as temperature and humidity, and if deviations exist, corresponding interventions are done. It can be inferred from the literature reviews that there is a need for accurate and large-scale measurement technology if production is to be carried out in a wide and automated form. Although the process of breeding BSF is quite well known in principle, it is, on a closer inspection - with its all substrates and all stages of development - highly complex. In addition to "basic variables" such as temperature and humidity, measuring other properties of the growing environment, such as carbon dioxide or ammonia content (the meaning of which is differently reflected in the literature), can be particularly useful in some situations.

Improving the efficiency of the production process by interventions and control techniques implemented by measurement technology, is a particularly interesting topic. If the application of measurement technology at different stages of the growing process is effortless and the measured data is easy to routinely record, the data collected cumulatively from different breeding batches may enable systematic and even algorithmic identifications of the optimal growth processes based on the data collected. In the simplest form, this may be an ordinary quality control and review by experts about the correspondence between breeding conditions and the result of production. The measurements data may include answer for the question what were the essential characteristics of the measurement results during the breeding of the high-quality and large-yield production result?

Further, a particularly interesting perspective about the possible benefits of measurement technology in optimizing the production process is if the measurement technology could be used simultaneously during breeding to observe both growth conditions and growth results. In the most active stages, the growth process with its physical phenomena is very fast – at best, the larvae grow almost with a speed possible to see by the eyes. Measuring growth conditions in terms of temperature, humidity and the like properties is straightforward, but measuring corresponding growth results is naturally more difficult, but may still be somehow possible by applying, for example, artificial intelligence supported camera technology. Several strategies to measure the growth of insects in real time exist and the corresponding methods are evolving rapidly. If it would be possible to achieve detailed and reliable real-time information about the growth result during the breeding process, this may lead to big leaps in the optimization of breeding processes in BSF production.

BSF development process under typical conditions is quite predictable. The first task of sensing is the detection of deviations requiring an intervention. This can be based on outlier detection methods. Many recorded parameters vary over time and might have relatively large measuring error (Parodi *et al.*, 2020, Pang *et al.*, 2021) and therefore anomaly detection is likely to benefit from process modelling. The second task is to predict the development stage particularly for the larva, where the environment has more inherent variation due to feedback loops and precise timing has impact on product quality. Larvae are ready to be harvested after 10–12 days, before they turn into prepupae. At this stage, the larvae have reached their maximum weight, but have not yet transformed into prepupae and their nutritional value is at its maximum. Harvesting is the process in which the larvae are separated from the residue, e.g., by a shaking or drum sieve (Popoff and Maquart, 2016; Cheng *et al.*, 2017; Dortmans *et al.*, 2017) followed by blanching or other kill method (Erens *et al.*, 2012) and other processing (Larouche, 2019). and with prediction and environment adjustment product quality and equipment use load can be optimized.

Table 4 provides some information on the costs of BSF production. Sensing and automation can influence the economics of insect rearing in different ways. On one hand, sensing can help to increase production performance and viability of insects and on the other hand, automation can save work and enable the management of larger quantities of insects. Because feed and energy can be major components of production costs of BSF (for example, Ites *et al.* (2020) identified feed at the main cost component), it is essential that the insects use the feed efficiently and achieve a high feed conversion efficiency. Information on feed qualities such as nutritional content, moisture and pH can therefore provide valuable information on the success of BSF rearing. In addition, the weight of the crate at different points in time and environmental parameters such as the temperature of substrate are essential because they can provide indirect information about the growth of a batch. Temperature can also help in optimising the timing of harvesting, because the optimal harvesting is likely soon after the temperature of the substrate and the batch is starting to decrease. Other economically important parameters to be monitored include for example larval survival rate.

Table 4. Prices of H. Illucens larvae (fresh weight) and operational costs of rearing as presented in scientific literature (table modified from Niyonsaba et al., 2021).

Country	Price, €/t fresh	Larvae type	Operational cost, €/t dried larvae[1]	Reference
Egypt	427	Meal	na	Abdel-Tawwab *et al.* (2020)
Kenya	464	Meal	na	Chia *et al.* (2019)
Germany	6,500-18,190	Pet food, dried	3777	Ites *et al.* (2020)
Spain	2,273-5,091	Meal	na	Llagostera *et al.* (2019)
Italy	2,000/2,500	Meal/dried	na	Mancuso *et al.* (2019)
Germany	1,816	Dried	1452	Pleissner and Smetana (2020)
the Netherlands	2,000-3,000	Fresh	na	Hilkens *et al.* (2016)

1 Operational costs may include: feed, water, electricity, labour, gas

2.5 Concluding remarks

BSF development process under typical conditions is quite predictable even if the duration of the process varies substantially depending on environmental parameters sch as temperature. Many recorded parameters vary over time and might have relatively large measuring error and therefore anomaly detection is likely to benefit from process modelling.

BSF are generally monitored at container or population level rather than individual level. Important parameters to be monitored include temperature, humidity, air pressure, (bio)chemical and gases can be used to maintain a benign environment and substrate condition. Some insects' parameters can show substantial variation. For example, the coefficient of variation for prepupa and pupa developmental time, prepupal weight, waste reduction index or feed conversion ratio is around 40% or higher (Table 1). Hence, if high negative changes are measured in these parameters, they provide guidance on how to enhance the biological production process. The monitoring is expected to observe environmental deviations that are compromising a successful production process as well as to forecast the progress of insect rearing as a process. Additional information on substrate quality such as nutritional content and pH can also provide valuable information on the success of BSF rearing. Many environmental parameters, especially temperature and humidity, by contrast can vary by just 5-10% from the desired value without the production performance being impaired (see Table 3 for details). Small deviations in the key environmental parameters can result is substantial changes in some key performance indications of insects.

An additional factor that needs to be taken into account is that the rearing conditions vary by development stage of BSF and the fly stages have biological unique needs. Therefore, diverse sensing approaches are needed to evaluate the performances of BSF. Besides basic environmental information, more advanced technologies can also be utilized. For example, machine vision and other imaging technologies can be used to monitor different features such as hatching and oviposition performance as female activity, the number, activity and condition of neonate larvae, prepupae, pupae and adults, egg mortality and the condition of substrate. Motion that can be measured by monitoring the batch (e.g. crate) can provide information on activity and the status of insect population, whereas changes in the weight of the batch and the substrate can provide indications on the growth of insects and their mortality.

2.6 References

Abdel-Tawwab, M., Khalil, R.H., Metwally, A.A., Shakweer, M.S., Khallaf, M.A., Abdel-Latif H.M. 2020. Effects of black soldier fly (Hermetia illucens L.) larvae meal on growth performance, organs-somatic indices, body composition, and hemato-biochemical variables of European sea bass, Dicentrarchus labrax. Aquaculture 522: 735136. https://doi.org/10.1016/j.aquaculture.2020.735136

Alattar, M., Alattar, F., Popa, R. 2016. Effects of microaerobic fermentation and black soldier fly larvae food scrap processing residues on the growth of corn plants (*Zea mays*). Plant Sci. Today 3:57–62.

Alvarez, L. 2012. The role of black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae) in sustainable waste management in northern climates. PhD dissertation. University of Windsor.

Banks, I.J. 2014. To assess the impact of black soldier fly (*Hermetia illucens*) larvae on faecal reduction in pit latrines. PhD dissertation. London School of Hygiene & Tropical Medicine.

Banks, I.J., Gibson, W.T., Cameron, M.M. 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation, Tropical Medicine & International Health 19: 14–22.

Barragán-Fonseca, K. B., Dicke, M., van Loon, J.J. A. 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review. J. Insects Food Feed 3, 105–120.

Barragán-Fonseca, K.B., Dicke, M., van Loon J.J. 2018. Influence of larval density and dietary nutrient concentration on performance, body protein, and fat contents of black soldier fly larvae (*Hermetia illucens*). Entomol. Exp. Et Appl. 166:761–770.

Barry, T. 2004. Evaluation of the economic, social, and biological feasibility of bioconverting food wastes with the black soldier fly (*Hermetia illucens*). PhD dissertation. University of North Texas.

Beesigamukama, D., Mochoge, B., Korir, N., Fiaboe, K., Nakimbugwe, D., Khamis, F., Subramanian, S., Musyoka, M., Dubois, T., Ekesi, S., Tanga, C. 2021. Low-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly. Waste Management. 119:183–194. 10.1016/j.wasman.2020.09.043.

Beesigamukama, D., Mochoge, B., Korir, N., Musyoka, M.W., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Subramanian, S., Dubois, T., Ekesi, S., Tanga, C.M. 2020c. Nitrogen Fertilizer Equivalence of Black Soldier Fly Frass Fertilizer and Synchrony of Nitrogen Mineralization for Maize Production. Agronomy 10, 1395.

Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Dubois, T., Subramanian, S. Wangu, M.M. Ekesi, S., Tanga, C.M. 2020a. Biochar and gypsum amendment of agro-industrial waste for enhanced black soldier fly larval biomass and quality frass fertilizer. PLoS ONE 15, e238154.

Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Subramanian, S., Dubois, T., Musyoka, M.W., Ekesi S., Kelemu, S., Tanga, C.M. 2020b. Exploring Black Soldier Fly Frass as Novel Fertilizer for Improved Growth, Yield, and Nitrogen Use Efficiency of Maize Under Field Conditions. Front. Plant Sci. 11.

Boccazzi, I.V., Ottoboni, M., Martin, E., Comandatore, F., Vallone, L., Spranghers, T., Eeckhout, M., Mereghetti, V., Pinotti, L., Epis, S. 2017. A survey of the mycobiota associated with larvae of the black soldier fly (*Hermetia illucens*) reared for feed production. *PLoS One 12*, 1–15, doi:10.1371/journal.pone.0182533.

Bondari, K., Sheppard, D.C. 1981. Soldier fly larvae as feed in commercial fish production. Aquaculture 24: 103–109.

Bondari, K., Sheppard, D.C. 1987. Soldier fly, *Hermetia illucens* L., larvae as feed for channel catfish, *Ictalurus punctatus* (Rafinesque), and blue tilapia, *Oreochromis aureus* (Steindachner). Aquaculture and Fisheries Management 18: 209–220.

Booth, D.C., Sheppard, C. 1984. Oviposition of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae): Eggs, masses, timing, and site characteristics. Environmental Entomology 13: 421–423.

Briscoe, A.D., Chittka, L. 2001.The Evolution of Color Vision in Insects. Annual Review of Entomology 2001 46:1, 471–510.

Bulak, P., Polakowski, C., Nowak, K., Waśko, A., Wiącek, D., Bieganowski, A. 2018. *Hermetia illucens*as a new and promising species for use in entomoremediation. Science of the Total Environment 633: 912–919.

Bullock, N., Chapin, E., Evans, A., Elder, B., Givens, M., Jeffay, N., Pierce, B., Robinson, W. 2013. The Black Soldier Fly How-to-Guide, ENST 698-Environmental Capstone, Spring 2013. https://ie.unc.edu/wp-content/uploads/sites/277/2016/03/bsfl_how-to_guide.pdf

Cadinu L.A., Barra P., Torre F., Delogu F., Madau F.A. 2020. Insect rearing: Potential, challenges, and circularity. Sustainability 12, 4567.

Cammack, J.A., Tomberlin, J.K. 2017. The impact of diet protein and carbohydrate on select life-history traits of the black soldier fly *Hermetia illucens* (L.) (Diptera: Stratiomyidae). Insects 8: 56-69.

Caruso, D., Devic, E., Subamia, W.I., Talamond, P., Baras, E. (ed.) 2013. Technical handbook of domestication and production of Diptera Black Soldier Fly (BSF) *Hermetia illucens*, Stratiomyidae. PT Penerbit IPB Press, Kampus IPB Taman Kencana Bogor. 159 s. ISBN: 978-979-493-610-8.

Cheng, J.Y.K., Chiu, S.L.H., Lo, I.M.C. 2017. Effects of moisture content of food waste on residue separation, larval growth and larval survival in black soldier fly bioconversion. Waste Management 67: 315–323.

Chia, S.Y., Tanga, C.M., Khamis, F.M., Mohamed, S.A., Salifu, D., Sevgan, S., Fiaboe, K.M., Niassy, S., van Loon, J.J.A., Dicke, M., Ekesi, S. 2018. Threshold temperatures and thermal requirements of black soldier fly *Hermetia illucens*: Implications for mass production. PLoS ONE 13(11): e0206097. https://doi.org/10.1371/journal.pone.0206097.

Chia, S.Y., Tanga, C.M., Osuga, I.M., Alaru, A.O., Mwangi, D.M., Githinji, M., Subramanian, S., Fiaboe, K.K., Ekesi, S., Van Loon, J.J., 2019. Effect of dietary replacement of fishmeal by insect meal on growth performance, blood profiles and economics of growing pigs in Kenya. Animals 9: 705. https://doi.org/10.3390/ani9100705

Cho, S., Kim, C.H., Kim, M.J., Chung, H. 2020. Effects of microplastics and salinity on food waste processing by black soldier fly (*Hermetia illucens*) larvae. J. Ecol. Environ. 44:1–9.

Choi, Y.-C., Choi, J.-Y., Kim, J.-G., Kim, M.-S., Kim, W.-T., Park, K.-H., Bae, S.-W., Jeong, G.-S. 2009. Potential usage of food waste as a natural fertilizer after digestion by *Hermetia illucens* (Diptera: *Stratiomyidae*). Int. J. Ind. Entomol. 2009, 19, 171–174.

Cicková, H., Newton, G.L., Lacy, C., Kozánek, M. 2015. The use of fly larvae for organic waste treatment. Waste Management 35: 68–80.

Cloutier, J. 2015. Edible insects in Africa: An introduction to finding, using and eating insects. Agrodok 54. Agromisa Foundation and CTA, Wageningen. 80 s. ISBN 978-90-8573-146-7. https://hdl.handle.net/10568/73150.

Cohen, A. 2018. Ecology of Insect Rearing Systems: A Mini-Review of Insect Rearing Papers from 1906-2017. Advances in Entomology, 6, 86-115. doi: 10.4236/ae.2018.62008.

Diclaro, II J.W., Kaufman, P.E. 2009. Black soldier fly *Hermetia illucens* Linnaeus (Insecta: Diptera: Stratiomyidae). EENY-461, University of Florida, Gainesville. 4 s. https://edis.ifas.ufl.edu/in830.

Diener, S. 2010. Valorisation of organic solid waste using the black soldier fly, *Hermetia illucens*. Low and middle-income countries. PhD thesis, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf, Switzerland.

Diener, S., Roa Gutiérrez, F., Zurbrügg, C., Tockner, K. 2009a. Are larvae of the black soldier fly – *Hermetia illucens* - a financially viable option for organic waste management in Costa Rica? In: Proceedings 12th International Waste Management and Landfill Symposium, 5–9 October 2009, Sardinia, Italy.

Diener, S., Zurbrügg, C., Tockner, K. 2009b. Conversion of organic material by black soldier fly larvae: Establishing optimal feeding rates. Waste Management & Research 27: 603–610.

Diener, S., Studt, S., Nandayure, M., Roa Gutiérrez, F., Zurbrügg, C., Tockner, K. 2011a. Biological treatment of municipal organic waste using black soldier fly larvae. Waste Biomass Valorisation 2: 357–363.

Diener, S., Zurbrügg, C., Gutiérrez, F.R., Nguye,n D.H., Morel, A., Koottatep, T., Tockner, K. 2011b. Black soldier fly larvae for organic waste treatment—prospects and constraints. In Proceedings of the WasteSafe 2011-2nd International Conference, Khulna, Bangladesh, 13–15 February 2011; pp. 1–8.

Diener, S., Zurbrügg, C., Tockner, K. 2015. The potential use of the black soldier fly (Diptera: Stratiomyidae) as animal feed: Bioaccumulation of heavy metals and effects on the life cycle. Journal of Insects as Food and Feed 1(4): 261–270.

Dillon, R.J., Dillon, V.M. 2004. The Gut Bacteria of Insects: Nonpathogenic Interactions. Annual Review of Entomology, 49, 71–92.

Dortmans, B. 2015. Valorisation of organic waste – effect of the feeding regime on process parameters in a continuous black soldier fly larvae composting system. MSc thesis. SLU, Swedish University of Agricultural Sciences.

Dortmans, B., Diener, S., Verstappen, B.M., Zurbrügg, C. 2017. Black soldier fly biowaste processing - a step-by-step guide. Dübendorf, Switzerland: Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Dzepe, D., Nana, P., Kuietche, H.M., Kimpara, J.M., Magatsing, O., Tchuinkam, T., Djouaka, R. 2021. Feeding strategies for small-scale rearing black soldier fly larvae (*Hermetia illucens*) as organic waste recycler. SN Applied Sciences 3:252 | https://doi.org/10.1007/s42452-020-04039-5.

Erens, J., van E, S., Haverkort, F., Kapsomenou, E., Luijben, A. 2012. A Bug's Life. Large-scale insect rearing in relation to animal welfare. Wageningen University, Wageningen. 57 s. http://venik.nl/site/wp-content/uploads/2013/06/Rapport-Large-scale-insect-rearing-in-relation-to-animal-welfare.pdf.

Erickson, M.C., Islam, M., Sheppard, C., Liao, J., Doyle, M.P. 2004. Reduction of *Escherichia coli* O157:H7 and *Salmonella enterica* Serovar Enteritidis in chicken manure by larvae of the black soldier fly. Journal of Food Protection 67(4): 685–690.

Ermolaev, E., Lalander, C., Vinnerås, B. 2019. Greenhouse gas emissions from small-scale fly larvae composting with *Hermetia illucens*, Waste Management, Volume 96, 2019, Pages 65-74, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2019.07.011.

Fatchurochim, S., Geden, C., Axtell, R. 1989. Filth fly (Diptera) oviposition and larval development in poultry manure of various moisture levels. Journal of Entomological Science 24: 224–231.

Furman, D.P., Young, R.D., Catts, E.P. 1959. *Hermetia illucens* (Linnaeus) as a factor in the natural control of Musca domestica Linnaeus. Journal of Economic Entomology 52(5): 917–921.

Georgescu, B., Struti, D., Papuc, T., Ladosi, D., Boaru, A. 2020. Body weight loss of black soldier fly Hermetia illucens (Diptera: Stratiomyidae) during development in non-feeding stages: Implications for egg clutch parameters. Eur. J. Entomol. 117: 216–225. https://doi.org/10.14411/eje.2020.023

Gobbi, F.P. 2012. Biología reproductiva y caracterización morfológica de los estadios larvarios de *Hermetia illucens* (L., 1758) (Diptera: Stratiomyidae). Bases para su producción masiva en Europa. PhD thesis, Universidad de Alicante, Alicante, Spain.

Gobbi, P., Martínez-Sánchez, A., Rojo, S. 2013. The effects of larval diet on adult life-history traits of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). European Journal of Entomology 110:461–468.

Gougbedji, A., Agbohessou, P., Laleye, P.A., Francis, F., Medigo, R.C. 2021. Technical basis for the small scale production of black soldier fly *Hermetia illucens* (L. 1758) meal as fish feed in Benin. Journal of Agriculture and Food Research. 4:100153. DOI: 10.1016/j.jafr.2021.100153.

Hale, O.M. 1973. Dried *Hermetia illucens* larvae (Diptera, Stratiomyidae) as a feed additive for poultry. Journal of Georgia Entomological Society 8(1): 17–20.

Hansen, L.L., Westh, P., Wright, J.C., Ramløv, H. 2006. Metabolic changes associated with active water vapour absorption in the mealworm *Tenebrio molitor* L. (Coleoptera, Tenebrionidae): a microcalorimetric study. J Insect Physiol. Mar. 52(3): 291-9. doi: 10.1016/j.jinsphys.2005.11.008. Epub 2006 Jan 10. PMID: 16412458.

Harnden, L.M., Tomberlin, J.K. 2016. Effects of temperature and diet on black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae), development. Forensic Science International 266: 109–116.

Heussler, C.D., Walte,r A., Oberkofler, H., Insam, H., Arthofer, W., Schlick-Steiner, B.C., Steiner, F.M. 2018. Influence of three artificial light sources on oviposition and half-life of the Black Soldier Fly, *Hermetia illucens* (Diptera: Stratiomyidae): Improving small-scale indoor rearing. PLoS ONE 13(5): e0197896. https://doi.org/10.1371/journal.pone.0197896.

Hilkens, W., De Klerk, B., Van Gestel, D., 2016. Insect farming: small sector with big opportunities. Insectenkweek: kleine sector met grote kansen. ABN AMRO/Brabantse Ontwikkelings Maatschappij, Amsterdam/Tilburg, the Netherlands, 37 pp.

Hoc, B., Noël, G., Carpentier, J., Francis, F., Caparros Megido, R. 2019. Optimization of black soldier fly (*Hermetia illucens*) artificial reproduction. PLoS ONE 14(4): e0216160. https://doi.org/10.1371/journal.pone.0216160.

Hogsette, J. A. 1992. New diets for production of house flies and stable flies (Diptera: Muscidae) in the laboratory. Journal of Economic Entomology 85: 2291–2294.

Holmes, L.A., VanLaerhoven, S.L., Tomberlin, J.K. 2017. Photophase Duration Affects Immature Black Soldier Fly (Diptera: Stratiomyidae) Development. Environmental Entomology 2017 Dec 8;46(6):1439-1447. doi: 10.1093/ee/nvx165. PMID: 29069348.

Holmes, L. 2010. Role of abiotic factors on the development and life history of the black soldier fly, *Hermetia illucens* (L.) (Diptera: Stratiomyidae). MSc Thesis. University of Windsor, Windsor. 168 s.

Holmes, L., VanLaerhoven, S., Tomberlin, J., 2016. Lower temperature threshold of black soldier fly (Diptera: Stratiomyidae) development. Journal of Insects as Food and Feed 2: 1–8.

Holmes, L.A, Vanlaerhoven, S.L., Tomberlin, J.K. 2012. Relative humidity effects on the life history of *Hermetia illucens* (Diptera: Stratiomyidae). Environmental Entomology 41(4): 971–978.

Holmes, L.A., Vanlaerhoven, S.L., Tomberlin, J.K. 2013. Substrate effects on pupation and adult emergence of *Hermetia illucens* (Diptera: Stratiomyidae). Environmental Entomology 42: 370–374.

Inglis, G.D., Sikorowski, P.P. 2009. Entomopathogens and Insect Rearing. In: Schneider, J.C., Ed., Principles and Procedures for Rearing High Quality Insects, Mississippi State University, MS State, 223–288.

Ites, S., Smetana, S., Toepfl, S., Heinz, V. 2020. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. Journal of Cleaner Production 248: 119248. https://doi.org/10.1016/j.jclepro.2019.119248

Jansen, J., Hendrikus, A., Schol, B., Jürgens, F. 2019. Insect Breeding Device. Available online: https://patentimages.storage.googleapis.com/f8/33/0c/b5072cba2cb2a2/WO2019125165A1.pdf

Joly, G., Nikiema, J. 2019. Global experiences on waste processing with black soldier fly (Hermetia illucens): from technology to business. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 62p. (Resource Recovery and Reuse Series 16) doi: 10.5337/2019.214.

Kaleka, A.S., Kaur, N., Bali, G.K. 2019. Larval Development and Molting. In Edible Insects. IntechOpen. https://www.intechopen.com/online-first/larval-development-and-molting.

Kelemu, S., Niassy, S., Torto, B., Fiabo, K., Aognon, H., Tonnang, H., Maniania, N.K., Ekesi, S. 2015. African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. Journal of Insects as Food and Feed 1, 103–119.

Khan, S.H. 2018. Recent advances in role of insects as alternative protein source in poultry nutrition. Journal of Applied Animal Research 46:1, 1144-1157, DOI:10.1080/09712119.2018.1474743.

Kim, C.-H., Ryu, J., Lee, J., Ko, K., Lee, J.-y., Park, K.Y., Chung, H. 2021. Use of Black Soldier Fly Larvae for Food Waste Treatment and Energy Production in Asian Countries: A Review. Processes 9(1):161. https://doi.org/10.3390/pr9010161.

Kinasih, I., Putra, R. E., Permana, A. D., Gusmara, F.F., Nurhadi, M.Y., Anitasari, R. A. 2018. Growth performance of black soldier fly larvae (*Hermetia illucens*) fed on some plant based organic wastes. HAYATI Journal of Biosciences 25(2), 79–84. https://doi.org/10.4308/hjb.25.2.79.

Klammsteiner, T., Turan, V., Fernández-Delgado, J.M., Oberegger, S., Insam, H. 2020a. Suitability of Black Soldier Fly Frass as Soil Amendment and Implication for Organic Waste Hygienization. Agronomy 10(10), 1578. https://doi.org/10.3390/agronomy10101578K

Klammsteiner, T., Walter, A., Bogataj, T., Heussler, C.D., Stres, B., Steiner, F.M., Schlick-Steiner, B.C., Arthofer, W., Insam, H. 2020b. The core gut microbiome of black soldier fly (*Hermetia illucens*) larvae raised on low-bioburden diets. Frontiers in Microbiology 11, 993.

Klunder, H.C., Wolkers, R.J., Korpela, J.M., Nout, M.J.R. 2012. Microbiological aspects of processing and storage of edible insects. Food Control 26, 628–631.

Kortelainen, T., Siljander-Rasi, H., Tuori, M., Partanen, K. 2014. Ileal digestibility of amino acids in novel organic protein feedstuffs for pigs : black soldier fly larvae meal (*Hermetia illucens*). Helsinki, Finland. http://urn.fi/URN:NBN:fi-fe201603298909.

Kröncke, N., Baur, A., Böschen, V., Demtroder, S., Benning, R., Delgado, A. 2020. Automation of Insect Mass Rearing and Processing Technologies of Mealworms (*Tenebrio molitor*). In book: African Edible Insects As Alternative Source of Food, Oil, Protein and Bioactive Components. DOI: 10.1007/978-3-030-32952-5_8. (only abstract).

Kwon, J.H., Kim, J.Y. 2016. Treatment efficiency of food waste by the black soldier fly (*Hermetia illucens*) depending on salinity and moisture contents. Journal of Korea Society of Waste Management 33(6), 590–597.

Kyntäjä, S. Partanen, K., Siljander-Rasi, H., Jalava, T. 2014. Tables of composition and nutritional values of organically produced feed materials for pigs and poultry. MTT Report 164, MTT, Helsinki, Finland. Available at: http://www.mtt.fi/mttraportti/pdf/mttraportti164.pdf.

Lai, D., Gu, D., Huang, X., Su, K. 2020. Breeding device and breeding system. Patent CN111328772A. Available online: https://patents.google.com/patent/CN111328772A/en.

Lalander, C., Ermolaev, E., Wiklicky, V., Vinnerås, B. 2020. Process efficiency and ventilation requirement in black soldier fly larvae composting of substrates with high water content. Science of The Total Environment 759, 144422. https://doi.org/10.1016/j.scitotenv.2020.144422.

Lalander, C., Diene, S., Magri, M.E., Zurbrügg, C., Lindström, A., Vinnerås, B. 2013. Faecal sludge management with the larvae of the black soldier fly (*Hermetia illucens*) — from a hygiene aspect. Science of the Total Environment 458-460, 312–318.

Lalander, C., Diener, S., Zurbrügg, C., Vinnerå,s B. 2018. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). Journal of CleanerProduction 208, 211-219.

Lalander, C., Fidjeland, J., Diener, S., Eriksson, S., Vinnerås, B. 2015. High waste-to- biomass conversion and efficient Salmonella spp. reduction using black soldier fly for waste recycling. Agronomy for Sustainable Development 35, 261–271.

Lardé, G. 1989. Investigation on some factors affecting larval growth in a coffeepulp bed. Biological Wastes 30, 11–19.

Larouche, J. 2019**.** Processing methods for the black soldier fly (*Hermetia illucens*) larvae : From feed withdrawal periods to killing methods. *Master thesis*.

Leong, S.Y., Kutty, S.R.M., Tan, C.K., Tey, L.H. 2015. Comparative study on the effect of organic waste on lauric acid produced by *Hermetia illucens* larvae via bioconversion. Journal of Engineering Scienceand Technology Special Issue on ACEE 2015 Conference, August 2015. eFrom organic waste to biodiesel: Black soldierfly, *Hermetia illucens*, makes it feasible. Fuel 90, 1545–1548.

Li, C.-J., 2014. Conversion of spent grains and DDGS by black soldier flies. MSc thesis, Laboratory of Entomology, Wageningen University, Wageningen, the Netherlands.

Li, B., Qu, J. 2021. Efficient breeding feed for *Hermetia illucens* and breeding method thereof. Patent CN112741234A. Available online: https://patents.google.com/patent/CN112741234A/en.

Li, Q., Zheng, L., Qiu, N., Cai, H., Tomberlin, J.K., Yu, Z. 2011a. Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production. Waste Management 31(6), 1316–1320.

Li, Q., Zheng, L., Qiu, N., Cai, H., Yu, Z., Zhou, S. 2011b. From organic waste to biodiesel: Black soldier fly, *Hermetia illucens*, makes it feasible. Fuel 90, 1545–1548.

Li, W., Li, Q., Zheng, L., Wang, Y., Zhang, J., Yu, Z., Zhang, Y. 2015. Potential biodiesel and biogas production from corncob by anaerobic fermentation and black soldier fly. Bioresource Technology 194, 276–282.

Liu, Q., Tomberlin, J.K., Brady, J.A., Sanford, M.R., Yu Z. 2008. Black soldier fly (Diptera: Stratiomyidae) larvae reduce *Escherichia coli* in dairy manure. Environmental Entomology 37(6), 1525–1530.

Llagostera, P.F., Kallas, Z., Reig, L., De Gea, D.A., 2019. The use of insect meal as a sustainable feeding alternative in aquaculture: current situation, Spanish consumers' perceptions and willingness to pay. Journal of Cleaner Production 229, 10-21. https://doi.org/10.1016/j.jclepro.2019.05.012

Lohri, C.R., Diener, S., Zabaleta, I., Mertenat, A., Zurbrügg, C. 2017. Treatment technologies for urban solid biowaste to create value products: a review with focus on low-and middle-income settings. Reviews in Environmental Science and Bio/Technology 16, 81–130.

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P. 2014. State-of-the-art on use of insects as animal feed. Animal Feed Science and Technology 197, 1–33.

Mancuso, T., Pippinato, L., Gasco, L., 2019. The European insects sector and its role in the provision of green proteins in feed supply. Calitatea 20, 374-381.

Manurung, R., Supriatna, A., Esyanthi, R.R., Putra, R.E. 2016. Bioconversion of rice straw waste by black soldier fly larvae (*Hermetia illucens* L.): Optimal feed rate for biomass production. Journal of Entomology and Zoology Studies 4(4), 1036–1041.

Massaro, P., Sobecki, R., Behling, C., Criswell ,V., Zha, T., Devengenzo, R. 2018. Automated mass rearing system for insect larvae. Patent WO 2018/067376 Al. Available online: https://patentimages.storage.googleapis.com/7e/f2/59/068769b27a3482/WO2018067376A1.pdf.

May, B., 1961. The occurrence in New Zealand and the life-history of the soldier fly *Hermetia illucens* (L.)(Diptera: Stratiomyidae). New Zealand Journal Science 4, 55-65.

Meuwissen, P., 2011. Insects as new protein source. A scenario exploration of market opportunities. Insecten als nieuwe eiwitbron. Een scenarioverkenning van de marktkansen. ZLTO, 's Hertogenbosch, the Netherland.

Miranda, C.D., Cammack, J.A., Tomberlin, J.K. 2020. Mass Production of the Black Soldier Fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae) Reared on Three Manure Types. Animals 10, 1243. https://doi.org/10.3390/ani10071243.

Mohd-Noor, S.-N., Wong, C.-Y., Lim, J.-W., Mah-Hussin, M.-I.-A., Uemur, Y, Lam, M.K., Ramli, A., Bashir, M.J.K., Tham, L. 2017. Optimization of self-fermented period of waste coconut endosperm destined to feed black soldier fly larvae in enhancing the lipid and protein yields. Renewable Energy 111, 646–654.

Mutafela, R.N. 2015. High value organic waste treatment via black soldier fly bioconversion (onsite pilot study). MSc thesis. KTH Royal Institute of Technology.

Myers, H.M., Tomberlin, J.K., Lambert, B.D., Kattes, D. 2008. Development of black soldier fly (Diptera: Stratiomyidae) larvae fed dairy manure. Environ. Entomol. 37(1), 11–15.

Nakamura, S., Ichiki, R.T., Shimoda, M., Morioka, S. 2016. Small-scale rearing of the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae), in the laboratory: low-cost and year-round rearing. Appl. Entomol. Zool. 51, 161–166.

Newton, G.L., Booram, C.V., Barker, R.W., Hale, O.M. 1977. Dried *Hermetia illucens* larvae meal as a supplement for swine. J. Anim. Sci. 44, 395–400.

Newton, G.L., Sheppard, D.C., Thompson, S.A., Savage, S.I. 1995. The soldier fly, a beneficial insect: House fly control, manure volume reduction and nutrient recycling. In: Proceedings nuisance concernsin animal manure management: Odors and flies conference. Gainesville FL: University of Florida. PRO107. Pp.106–116.

Newton, L., Sheppard, C., Watson, D.W., Burtle, G., Dove, R. 2005. Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure. North Carolina State University, Raleigh. 19 s.

Nguyen, T.T., Tomberlin, J.K., Vanlaerhoven, S. 2015. Ability of black soldier fly (Diptera: Stratiomyidae) larvae to recycle food waste, Environmental Entomology 44, 406–410.

Nguyen, T.T.X., Tomberlin, J.K., Vanlaerhoven, S. 2013. Influence of resources on *Hermetia illucens* (Diptera: Stratiomyidae) larval development. J. Med. Entomol. 50(4), 898–906.

Niyonsaba, H., Höhler, J. Kooistra, J., Van der Fels-Klerx, H, Meuwissen, M. 2021. Profitability of insect farms. Journal of Insects as Food and Feed 7, 923-934.

Nyakeri, E.M., Ayieko, M.A., Amimo, F.A., Salum, H., Ogola, H.J.O. 2019. An optimal feeding strategy for black soldier fly larvae biomass production and faecal sludge reduction. J Insects as Food Feed 5(3), 201–213; https://doi.org/10.3920/JIFF2018.0017.

Oonincx, D., Volk, N., Diehl, J., van Loon, J., Belusˇič G. 2016. Photoreceptor spectral sensitivity ofthe compound eyes of black soldier fly (*Hermetia illucens*) informing the design of LED-based illumination to enhance indoor reproduction. J Insect Physiol. 95,133–9. https://doi.org/10.1016/j.jinsphys.2016.10.006 PMID: 27751886.

Oonincx, D., van Huis, A., van Loon, J. 2015b. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. Journal of Insects as Food and Feed 1, 131–139.

Oonincx, D., van Itterbeeck, J., Heetkamp, M., van den Brand, H., van Loon, J., van Huis, A. 2010. An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption, PLoS ONE 5(12), 1–7. https:// doi.org/10.1371/journal.pone.0014445.

Oonincx, D.G.A.B., van Broekhoven, S., van Huis, A., van Loo, J.J.A. 2015a. Feed conversion, survivaland development, and composition of four insect species on diets composed of food by-products. PLOS ONE 10(12), e0144601. https://doi.org/10.1371/journal.pone.0144601.

Ortiz, J.A.C., Ruiz, A.T., Morales-Ramos, J.A., Thomas, M., Rojas, M.G., Tomberlin, J.K., Yi, L., Han, R., Giroud L., Jullien R.L. 2016. Chapter 6 - Insect mass production technologies. In: Dossey, A.T., Morales-Ramos, J.A. & Rojas, M.G. (toim.) Insects as sustainable food ingredients. Academic Press, San Diego. s. 153–201. ISBN 9780128028568.

Pang, W., Hou, D., Nowar, E.E., Chen, H., Zhang, J., Zhang, G., Li, Q., Wang, S. 2020. The influence on carbon, nitrogen recycling, and greenhouse gas emissions under different C/N ratios by black soldier fly. Environ. Sci. Pollut. Res. doi:10.1007/s11356-020-09909-4.

Panizzi, A.R., Parra, J.R.P. 2012. Insect bioecology and nutrition for integrated pest management. In: Panizzi, A.P., Parra, J.R.P. (ed.) Contemporary Topics in Entomology. CRC Press, Boca Raton.

Parodi, A., Gerrits, W.J.J., Van Loon, J.J.A., De Boer, I.J.M., Aarnink, A.J.A., Van Zanten, H.H.E. 2021. Black soldier fly reared on pig manure: Bioconversion efficiencies, nutrients in the residual material, greenhouse gas and ammonia emissions. Waste Manag. 126, 674–683, doi:10.1016/j.wasman.2021.04.001.

Parra Paz, A.S., Carrejo, N.S., Gomez Rodriguez, C.H. 2015. Effects of larval density and feeding rates on the bioconversion of vegetable waste using black soldier fly larvae *Hermetia illucens* (L.) (Diptera: Stratiomyidae). Waste Biomass Valoriz. 6(6), 1059–1065.

Pastor, B., Velasques, Y., Gobbi, P., Rojo, S. 2015. Conversion of organic wastes into fly larval biomass: bottlenecks and challenges. Insects as Food and Feed 1,179–193.

Perednia, D.A. 2016. Using black soldier flies as a tool for rural and community development. Permetia Envirotech, Inc. Available at https://portal.nifa.usda.gov/web/crisprojectpages/1006293-using-black-soldier-flies-asa-tool-for-rural-and-community-development.html.

Pleissner, D., Smetana, S., 2020. Estimation of the economy of heterotrophic microalgae-and insect-based food waste utilization processes. Waste Management 102, 198-203. https://doi.org/10.1016/j.wasman.2019.10.031

Popoff, M., Maquart, P.-O. 2016. Ento Prise Ghana [Eng]. Video recording, YouTube. Available at https://www.youtube.com/watch?v=7pIkBz5lZvM&t=261s.

Putra, R.E., Margareta, A., Kinasih, I. 2020. The Digestibility of Banana Peel and Testa coconut and Its Effects on the Growth and Mortality of Black Soldier Fly Larvae (*Hermetia illucens*) at Constant Feeding Rates. Biosfer: Jurnal Tadris Biologi 11 (1), 66–77.

Quilliam, R.S., Nuku-Adeku, C., Maquart, P., Little, D., Newton, R., Murray, F. 2020. Integrating insect frass biofertilisers into sustainable peri-urban agro-food systems. J. Insects Food Feed 1–8.

Rachmawati, R., Buchori, D., Hidayat, P., Hem, S., Fahmi, M.R., 2010. Perkembangan dan kandungan nutrisi larva *Hermetia illucens* (linnaeus)(Diptera: Stratiomyidae) pada bungkil kelapa sawit. Jurnal Entomologi Indonesia 7, 28–41.

Rehman, K. ur, Cai, M., Xia, X., Zheng, L., Wang, H., Soomro, A.Az., Zhou, Y., Li, W., Yu, Z., Zhang, J. 2017a. Cellulose decomposition and larval biomass production from the co-digestion of dairy manureand chicken manure by mini-livestock (*Hermetia illucens* L.). Journal of Environmental Management 196, 458–465.

Rehman, K. ur, Rehman, A., Cai, M., Zheng, L., Xia, X., Soomro, A.A., Wang, H., Li, W., Yu, Z., Zhang, J. 2017b. Conversion of mixtures of dairy manure and soybean curd residue by black soldier fly larvae (*Hermetia illucens* L.). Journal of Cleaner Production 154, 366–373.

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D. 2017. Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using*Hermetia illucens*. Journal of Cleaner Production 140, 890–905.

Sandeepa, N., Thavarajah P. 2021. IOT For Agriculture. Available online: https://www.researchgate.net/publication/350213463_IOT_For_Agriculture.

Saragi, E.S., Bagastyo, A.Y. 2015. Reduction of organic solid waste by black soldier fly (*Hermetia illucens*) larvae. The 5th Environmental Technology and Management Conference “Green Technology towards Sustainable Environment” November 23-24, 2015, Bandung, Indonesia.

Sarpong, D., Oduro-Kwarteng, S., Gyasi, S.F., Buamah, R., Donkor, E., Awuah, E., Baah, M.K. 2019. Biodegradation by composting of municipal organic solid waste into organic fertilizer using the black soldier fly (*Hermetia illucens*) (Diptera: Stratiomyidae) larvae. Int. J. Recycl. Org. Waste Agric. 8, 45–54.

Sealey, W.M., Gaylord, T.G., Barrows, F.T., Tomberlin, J.K., Mcguire, M.A., Ross, C., St-Hilaire, S. 2011. Sensory analysis of rainbow trout, Oncorhynchus mykiss, fed enriched black soldier fly prepupae, *Hermetia illucens*. Journal of the World Aquaculture Society 42(1), 34–45.

Setti, L., Francia, E., Pulvirenti, A., Gigliano, S., Zaccardelli, M., Pane, C., Caradonia, F., Bortolini, S., Maistrello, L., Ronga, D. 2019. Use of black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae)larvae processing residue in peat-based growing media. Waste Manag. 95, 278–288. https://doi.org/10.1016/j. wasman.2019.06.017.

Sheppard, D.C., Newton, G.L., Burtle, G., 2008. Black soldier fly prepupae a compelling alternative to fish meal and fish oil. Public comment prepared in response to a request by the National Marine Fisheries Service Nov. 15, 2007, NOAA 15/11//2007-29/2/2008. Available at: http://tinyurl.com/l28f34a.

Sheppard, D.C., Newton, G.L., Thompson, S.A., Savage, S. 1994. A value added manure management system using the black soldier fly. Bioresource Technology 50, 275–279.

Sheppard, D.C., Tomberlin, J.K, Joyce, J.A., Kiser, B.C., Sumner, S.M. 2002. Rearing methods for the black soldier fly (Diptera: Stratiomyidae). J. Med. Entomol. 39 (4), 695–698.

Shumo, M., Osuga, I., Khamis, F., Tanga, C., Fiabo, K., Subramanian, S., Ekesi, S., Huis, A.V., Borgemeister C. 2019. The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. Scientific Reports 9 (1). https://www.nature.com/articles/s41598-019-46603-z.

Slone, D.H., Gruner, S.V. 2007. Thermoregulation in larval aggregations of carrion-feeding blow flies (Diptera: Calliphoridae). J Med Entomol. 44(3),516-23. doi: 10.1603/0022-2585

Schmitt, E., de Vries, W. 2020. Potential benefits of using *Hermetia illucens* frass as a soil amendment on food production and for environmental impact reduction. Current Opinion in Green and Sustainable Chemistry. https://doi.org/10.1016/j.cogsc.2020.03.005.

Spranghers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., De Meulenaer, B., Michiels, J., Eeckhout, M., De Clercq, P., De Smeta, S. 2017. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates, J. Sci. Food Agric. 97, 2594–2600.

St-Hilaire, S., Sheppard, C., Tomberlin, J.K., Irving, S., Newton, L., McGuire, M.A., Mosley, E.E., Hardy, R.W., Sealey, W. 2007a. Fly prepupae as a feedstuff for rainbow trout, Oncorhynchus mykiss. Journal of the World Aquaculture Society 38, 59–67.

Tomberlin, J.K., van Huis, A., Benbow, M.E., Jordan, H., Astuti, D.A., Azzollini, D., Banks, I., Bava, V., Borgemeister, C., Cammack, J.A., Chapkin, R.S., Cikova, H., Crippen, T.L., Day, A., Dicke, M., Drew, D., Emhart, C., Epstein, M., Finke, C M., Fischer, H., Gatlin, D., Grabowsk, N.T., He, C., Heckman, L., Hubert, A., Jacobs, J., Joseph, J., Khanal, S.K., Kleinfinger, J.K., Klein, G., Leach, C., Liu, Y., Newton, G.L., Olivier, R., Pechal, J.L. Picard, C.J., Rojo, S., Roncarati, A., Sheppard, C., Tarone, A.M., Verstappen, B., Vickerson, A., Yang, H., Yen, A., Yu, Z., Zhang, J., Zheng, L. 2015. Protecting the environment through insect farming as a means to produce protein for use as livestock, poultry, and aquaculture feed. Journal of Insects as Food and Feed 1, 307–309.

Tomberlin, J. K. 2001. Biological, behavioral, and toxicological studies on the black soldier fly (Diptera: Stratiomyidae). Ph.D. dissertation, University of Georgia, Athens.

Tomberlin, J.K., Sheppard, D.C. 2001. Lekking behavior of the black soldier fly (Diptera: Stratiomyidae). Florida Entomol. 84, 729–730.

Tomberlin, J.K., Sheppard, D.C. 2002. Factors influencing mating and oviposition of black soldier flies (Diptera: Stratiomyidae) in a colony. Journal of Entomological Science 37, 345–352.

Tomberlin, J.K., Sheppard, D.C., 2001. Lekking behavior of the black soldier fly (Diptera: Stratiomyidae). Florida Entomologist 84, 729–730.

Tomberlin, J.K., Adler, P.H., Myers, H.M. 2009. Development of the black soldier fly (Diptera: Stratiomyidae) in relation to temperature. Environ. Entomol. 38(3), 930–934.

Tomberlin, J.K., Sheppard, D.C., Joyce, J.A. 2002. Selected life-history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets. Annals of the Entomological Society of America 95, 379–386.

Tomberlin, J.K., Sheppard, D.C., Joyce, J.A. 2005. Black soldier fly (Diptera: Stratiomyidae) colonization of pig carrion in South Georgia. Journal of Forensic Sciences 50, 152–153.

Ussery, H. 2009. Black soldier fly, white magic. Backyard Poultry Magazine Oct/Nov 2009. https://www.themodernhomestead.us/article/Black+Soldier+Fly.html.

Vajpayee, P., Yogi, K.K. 2021. Recognition and Early Stage Detection of Phytophthora in a Crop Farm Using IoT. DOI: 10.5772/intechopen.97767. Available online: https://api.intechopen.com/chapter/pdf-preview/77361.

Vickerson, A., Radley, R., Marchant, B., Kaulfuss, O., Kabaluk, T. 2017. *Hermetia illucens* frass production and use in plant nutrition and pest management. Available online: https://patentimages.storage.googleapis.com/50/4f/b2/ce5509891ddcb1/US9844223.pdf.

Vogel, H., Müller, A., Heckel, D.G., Gutzeit, H., Vilcinskas, A. 2018. Nutritional immunology: Diversification and diet-dependent expression of antimicrobial peptides in the black soldier fly *Hermetia illucens*. Dev. Comp. Immunol. 78, 141–148, doi:10.1016/j.dci.2017.09.008.

Wang, Y.-S., Shelomi, M. 2017. Review of Black Soldier Fly (*Hermetia illucens*) as Animal Feed and Human Food. Foods 6,91. https://doi.org/10.3390/foods6100091.

Wang, X., Zhu, K.C.H. 2020. Automatic black soldier fly breeding and unloading system. Available online: https://patents.google.com/patent/CN111149777A/en.

Yang, J., Yang, Y., Wu, W., Zhao, J., Jiang, L. 2014. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environmental Science & Technology 48, 13776–13784. DOI: 10.1021/es504038a.

Yang, S. 2017. Intensive black soldier fly farming. Symton Black Soldier Fly Blog, entry posted July 30, 2017. Available at https://symtonbsf.com/blogs/blog.

Yang, S.-S., Brandon, A.M., Flanagan, J.C.A., Yang, J. Ning, D., Cai, S.-Y., Fan, H.-Q., Wang, Z.-Y., Ren, J., Benbow, E., Ren, N.-Q., Waymouth, R.M., Zhou, J., Criddle, C.S., Wu, W.-M. 2018. Biodegradation ofpolystyrene wastes in yellow mealworms (larvae of *Tenebrio molitor* Linnaeus): Factors affecting biodegradation rates and the ability of polystyrene-fed larvae to complete their life cycle. Chemosphere 191, 979–989. doi: 10.1016/j.chemosphere.2017.10.117.

Yu, G., Chen, P., Chen, Y., L, Y., Yang, Z., Chen, Y., Tomberlin, J.K. 2011. Inoculating poultry manurewith companion bacteria influences growth and development of black soldier fly (Diptera: Stratiomyidae) larvae. Environmental Entomology 40, 30–35.

Zhan, J., Huang, L., He, J., Tomberlin, J.K., Li, J., Lei, C., Sun, M., Liu, Z., Yu, Z. 2010. An artificial light source influences mating and oviposition of black soldier flies, *Hermetia illucens*. Journal of Insect Science 202(10), 1–7.

Zheng, L., Crippen, T.L., Holmes, L., Sing, B., Pimsler, M.L., Benbow, M.E., Tarone, A.M., Dowd, S., Yu, Z., Vanlaerhoven, S.L., Wood, T.K., Tomberlin, J.K. 2013. Bacteria mediate oviposition by the black soldier fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae). Nature Scientific Reports 3, 2563.

Zheng, L., Hou, Y., Li, W., Yang, S., Li, Q., Yu Z. 2012a. Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes. Energy 47, 225–229.

Zheng, L., Li, Q., Zhan, J., Yu, Z. 2012b. Double the biodiesel yield: Rearing black soldier fly larvae, *Hermetia illucens*, on solid residual fraction of restaurant waste after grease extraction for biodiesel production. Renewable Energy 41, 75–79.

Zhou, F. Tomberlin, J. K., Zheng, L., Yu, Z., Zhang, J. 2013. Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestockmanures. J. Med. Entomol. 50, 1224–1230. doi: 10.1603/me13021.

Zurbrügg, C., Dortmans, B., Fadhila, A., Vertsappen, B., Diener, S. 2018. From pilot to full scale operation of a waste-to-protein treatment facility. Detritus 01, 18–22.

3 House cricket (*Acheta domesticus*)

3.1 Bio-physical information on the rearing process

3.1.1 Basic information

Crickets are widely used as food in the world and have also been reared on an industrial scale in Western countries for decades to feed for domestic animals (Ortiz *et al.*, 2016). There are 900 species of crickets (van Huis, 2013). The house cricket can be considered one of the most promising novel foods in Europe, as it is an indigenous species in many European countries.

The nutrition and the rearing environments of house crickets is to some extent different from two other species considered in this deliverable. Therefore, obtaining specific knowledge on the desirable feeding and rearing conditions per insect species (and developmental stage) is important, because once the impact of each change in environmental or some other parameter on the insect rearing process (such as the weight and growth rate) is known, the insect production process can be modelled and optimized, and risks that may threaten the production while delivering quality cricket produce consistently can be controlled.

3.1.2 Life cycle

Crickets (Orthoptera) undergo incomplete metamorphosis with three distinct stages egg, nymph, and adult. Eggs hatch approximately 13 days after laying. Cricket metamorphosis is hemimetabolous, involving molting through 7 to 9 instars prior to reaching maturity. The amount of time spent within an instar is significantly influenced by temperature, humidity, and diet quality. The development from egg to adult takes about 45–60 days (6–9 weeks) (Clifford and Woodring, 1990; Finke and Oonincx, 2014; Hanboonsong and Durst, 2014; Cloutier, 2015). Except the egg stage, all stages occur in open air. Therefore, monitoring differs from black soldier fly. Four observations per hour is sufficient for monitoring these open-air stages, when alarms for deleterious extreme conditions are additionally set. The monitoring can mainly be based on ambient environment or remote sensing Figure 3. However, the production system's details might vary greatly from system to system and influence the recommended monitoring options. Crate groups might also be mixed at larval stage or in the mating stage, which makes detailed group ancestry documentation challenging.

3.1.3 Incubating and nursery period (0 to 14 days old)

The egg bowl is kept in an incubator with a temperature above 30 °C (Hanboonsong *et al.*, 2013; Clifford *et al.*, 1977). Eggs are white, thin and less than 1 mm long and hatch after 7 to 14 days if the temperature is steady and optimal (Hanboonsong *et al.*, 2013; Clifford *et al.*, 1977). The incubation time depends on the conditions (temperature and humidity). At room temperature incubation time is very long, but it decreases as the temperature increases (Table 5). When the first hatched crickets (pinheads) appear, they are initially as large as crickets' eggs. Pinheads are raised in the same way as older crickets, but they require higher humidity and temperature and fine, soft feed, which is high in protein (Hanboonsong and Durst, 2020).

Batches of first instars are separated to start new rearing units. The number of first instar per batch is estimated by volume (34 mL is equivalent to between 10,000 and 12,000 first instars). The number of first instars can also be estimated by weight. The mean weight of a first instar is approximately 500 µg, so 2000 first instars weigh approximately 1 g (Ortiz *et al.*, 2016).

The environment is non-liquid (gases, solid trays) and dark and the air is ventilated and circulated for homogenous conditions. However, heat and moisture may form a gradient from bottom to top and gas exchange can be less pronounced in the middle of the nymph tray. The youngest nymphs are often on top trays, and they descend to lower trays over time. One or two sets of ambient recording sensors (temperature, moisture, CO_2, possibly light) per chamber is enough to monitor for malfunctioning equipment. Otherwise, the condition distribution is a matter of incubation chamber design matter.

3.1.4 From 15 days of age until maturity

Nymphs undergo several molts before they reach adulthood. The number of molts varies from about 6 to 12 depending on the conditions (Nix and Bass, 1973; Patton 1978; Clifford and Woodring, 1990). According to Woodring *et al.* (1977), the maximum growth rate occurs in the first half of the 7th and 8th larval instars of the house cricket, at what time food and water consumption is maximal. Growth ceases in the last 2 to 3 days of each instar when food consumption is almost nil. On the other hand, the metabolic rate is twice and the locomotory activity is four times higher in the first 2–3 days than in the last 2–3 days of each instar. The percentage gain in dry weight is 120% for the 7th and 139% for the 8th instar (Woodring *et al.*, 1977). Cyclic variation in crickets' growth, feeding and drinking intensity according to molting stage and exponential growth of the last two larval stages of instars aids in monitoring the growth of crickets and determining the optimal ending time for cricket rearing, which is important factor for fully automated cricket farming systems (Entocube, 2021).

The environment of crickets is non-liquid (gases and solid items and potentially feed or frass traces) and follows a daylike L:D cycle and includes various obstacles (equipment and stimulating interior tiers) for visual monitoring (see Table 5). Heat, moisture, gases, and light might form gradients in the greater room, within the crates and around the tiers forming subspaces within the crate. Sensing solutions might vary between systems as some systems use small, closed and fully controlled crates, some midsized open or semi-closed crates and some crates are more pen type environments. For smaller crates one set of ambient sensors (temperature and moisture, potentially gases and light) is sufficient monitoring, while for pen type crates might benefit more from a wide spectrum camera surveillance. Insect activity can provide a proxy for environmental monitoring, and this can be done either by monitoring the placings and movements of crickets, or by detecting sounds or vibration levels and modeling their distribution in 3D. The latter methods require environment specific standards, while for physical direct measurements beneficial conditions are more clearly defined (see later). Observing the presence of dead insects requires movement tracking and may cover only parts of the crate, due to visual barriers. In addition, food and liquid use should be monitored and may be used to inform about animal activity, but the technical solutions depend on the exact equipment used. Generally, time series data is either beneficial or required depending on the trait (e.g., L:D –cycle, but also heat for monitoring the extent of heat stress requires a time series). Time series data are required to understand the lot's progress.

3.1.5 Adults

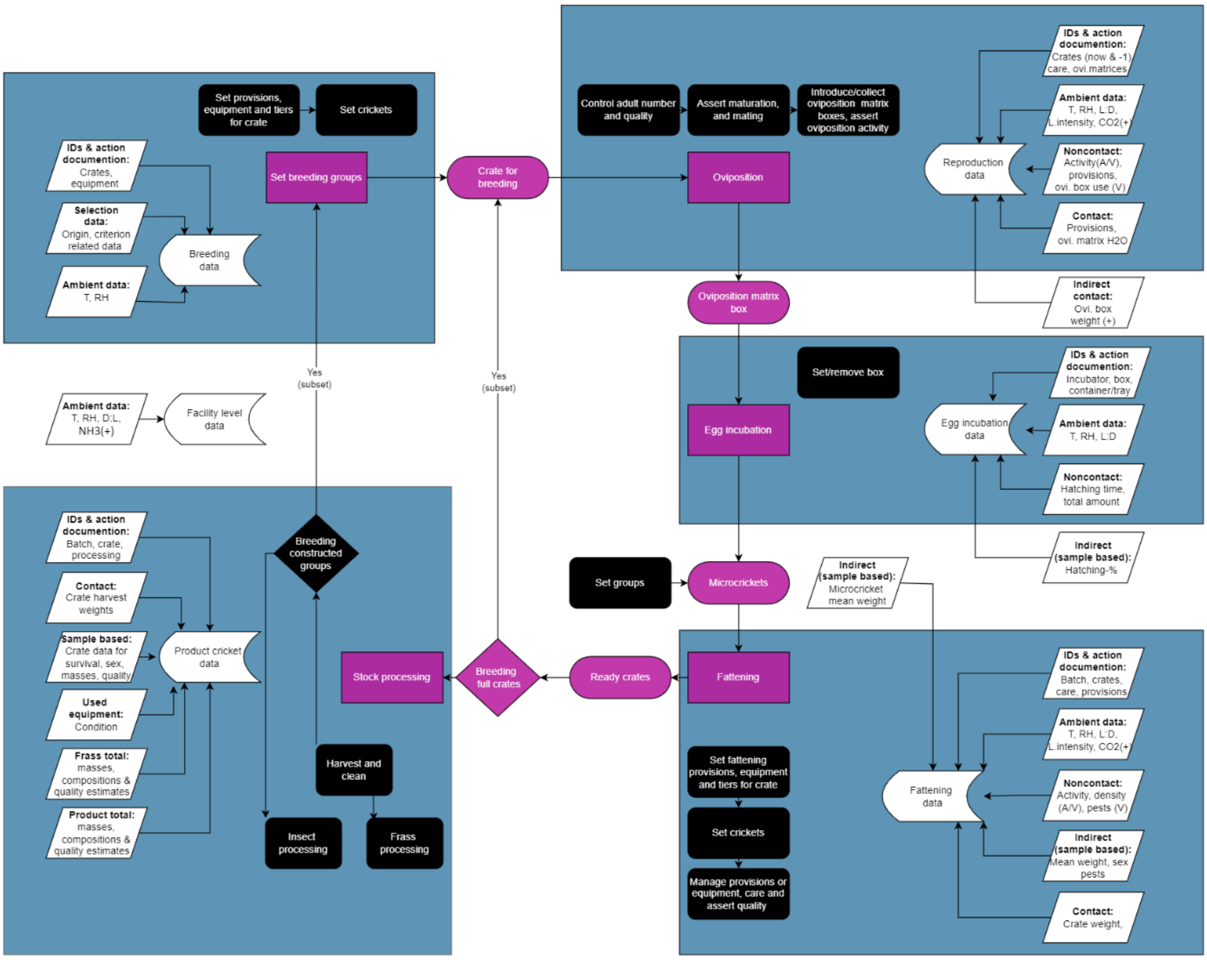
Adult crickets are identified by fully developed wings and chirping. The adult house cricket is about 2.5 cm long, light brown and has a black stripe between the eyes. Cricket bodies have three distinct segments: the head, the thorax, and the abdomen. They also have three pairs of legs and two antennae (Orinda *et al.*, 2020). The male is slightly smaller, and the female is easily recognized by the presence of an ovipositor (Cloutier, 2015).

Like other cricket species, mating of crickets relies on acoustic signals. Males make chirping sounds by rubbing their wings over each other (Huber, 1962). Each species has its own chirp and chirping is temperature dependent. Crickets chirp faster with increasing temperature (Walker, 1962). Female choice depends on the characteristics of the male signals, which reflect male quality (Nelson and Nolen, 1997). Males are ready to mate 2–3 days after adult emergence and become more effective with experience (Clifford and Woodring, 1990). Only mated females lay eggs and mating usually occurs two days after adult emergence.

Females will only oviposit if suitable oviposition media is available. One or more laying bowls with a layer of clean, moist, soft, porous material (about 3–5 cm deep) are placed in the rearing container to encourage egg laying (Cloutier, 2015). Oviposition media can contain mixed rice husks and sand (Hanboonsong *et al.*, 2013), mixture of sand and clay, potting soil, coconut fiber, cotton wool and peatmoss or other material that absorbs moisture (Clifford and Woodring, 1990; Cloutier, 2015). Vermiculite can be added to the material to avoid excessive moisture (Patton, 1978). The laying bowl is replaced and transferred to the warm container (hatching incubator) for every 24–72 hours (Hanboonsong *et al.*, 2013; Patton, 1978). New laying bowls are placed to the rearing container immediately or after few days.

The egg laying period begins on day 9 after reaching the adulthood and can last through 60 days, although peak in production occurs about day 15, with some females laying up to 200 eggs in one day (at 30°C) (Clifford and Woodring, 1986, 1990). In Thailand laying period lasts 7–14 days and reproduction cycle can be repeated one to three times for each generation (Hanboonsong *et al.*, 2013). Eggs can be collected for use in the farm for many cycles, but consideration must be given to avoiding inbreeding within the colony (Hanboonsong *et al.*, 2013; Hanboonsong and Durst, 2020). Adult lifespan lasts about 70 days (Clifford and Woodring, 1990). Crickets are active at night and during the day they hide in warm and dark places (Cloutier, 2015).

The environment is similar to the previous stage with two exceptions: adults chirp and egg laying requires specific oviposition places. Moreover, the mature animals, particularly the males, might be more sensitive to high animal density or requite more internal tiers for reduced stress. In addition to monitoring prolificacy, chirping activity can be monitored. Oviposition places are changed frequently and are unlikely to require monitoring for moisture. Their usage level is an indicator of breeding success and offer an option for visual monitoring. Otherwise, the general monitoring considerations are like in the previous stage.



T=temperature, RH=relative humidity, H2O=moisture, D:L=Dark:light cycle, L. = light, A=audio, V=visual, CO2=carbon dioxide, dm= dry mass, ovi.=oviposition.

Figure 3. Simplified flowchart sketching time-stamped sensing and tracking data that can be used for quality assurance and improvement for the biological house cricket production process. Technical flow chart is presented in D2.2 Figure 13.

3.1.6 Rearing conditions

Rearing conditions are expected to simulate the natural environments from which target insects are derived. Also breeding devices must be used which are especially adapted to the habits and character of the insects to be reared (Cohen, 2018). Rearing facilities should provide suitable conditions to allow insects to perform the reproductive functions that allow them to sustain continuous generations of offspring. These conditions include mating accommodations, suitable oviposition circumstances, and appropriate hatching and developmental requirements (Cohen, 2018).

Optimizing rearing conditions for house crickets increases the production efficiency and improves the well-being of the animals. Rearing conditions such as temperature, light-dark cycle, humidity, and available space influence the insect development (Fernandez-Cassi *et al.*, 2019). Unfavorable conditions can slow down development, promote abnormal behavior or increase insects' mortality rate (Clifford *et al.*, 1977; Tennis *et al.*, 1977; Clifford and Woodring, 1990; Parajulee *et al.*, 1993).

3.1.7 Temperature

Temperature is arguably the most important abiotic factor influencing the biology of insects. Because insects are poikilothermic and the body temperature changes with the ambient environmental temperatures, changes in ambient temperature can have substantial effect on the insect metabolism. House crickets originate from warm climate and accordingly develop fastest in relatively high temperatures (Table 5). Whilst crickets can survive temporary fluctuations in temperature, the eggs are less tolerant and require relatively consistent temperatures (Kvassay, 2014).

The influence temperature has on patterns of growth and development of insects has been particularly well studied and modelled (Booth and Kiddell, 2007; Wagner *et al.*, 1984; Liu *et al.*, 1995; Mirhosseini *et al.*, 2017; Rebaudo and Rabhi, 2018). The optimal rearing temperature for growing for house cricket is about 29–35 °C (Table 5). Although growth rates are increased by higher temperatures, adult size generally seems to decrease, a colder environment results in larger animals. According to Morales-Ramos *et al.* (2018), house cricket at 27 °C produced more biomass and adults were significantly larger than those developing at 29 °C. The optimal age to harvest based on food consumption and cricket biomass gain ratios was at the end of 8 weeks at 27 °C and at the end of 6 weeks at 29 °C (Morales-Ramos *et al.*, 2018).

In the study of Roe *et al.* (1980) the dry weight gain, total oxygen consumption, total food consumption, total water consumption, and several growth indices were not statistically different between the rearing temperatures of 30 and 35 °C. It is important to recognize that only temperatures above 35 °C (38–41 °C) cause near 100 % mortality (Ghouri and McFarlane, 1958). Heat generation inside the rearing container is an important issue as overheating can cause disease outbreaks and high death rates among the crickets (Hanboonsong and Durst, 2020).

Table 5. The desirable range of parameter values for A. domesticus.

Parameters	Range of favorable rearing conditions	Further notice	References
Rearing density	Minimum crawl space of 2.5 cm^2/cricket, 4–7 nymphs/dm^2.	Overcrowding may drastically affect the life cycle duration and physiological parameters.	Patton (1978), Clifford *et al.* (1977), Ortiz *et al.* (2016), Tennis *et al.* (1977).
Light, photoperiod	Nocturnal, adults have circadian rhythm in locomotor activity, feeding activity and oxygen consumption. Cycles of 12:12 and 14:10 L:D are recommended.	Continuous light interferes copulation.	Clifford *et al.* (1977), Clifford and Woodring (1990), Cohen (2015), Cymborowski (1973), Ghouri and McFarlane (1958), Górska-Andrzejak and Wojtusiak (2003), Nowosielski and Patton (1963), Oonincx *et al.* (2010), Woodring and Clifford (1986).
Temperature (°C)	Optimum 30 or 28–35 ± 0.5 °C. Incubation lasts 13 days at 30.5 °C, 14 days at 29,5°C, 16 days at 28 °C and 46–51 days at 23°C. All nymphal stages take 6–8 weeks at 32 °C. Last nymphal stage at 25 °C lasts 12–14 days, at 29.5°C 9 days, at 30.5 °C 8 days and at 35 °C 5–6 days.	Temperatures only slightly above 35 °C (38-41 °C) cause near 100% mortality. Eggs require relatively consistent temperatures.	Attard (2013), Booth and Kiddell (2007), Busvine (1955), Clifford *et al.* (1977), Clifford and Woodring (1990), Finke and Oonincx (2014), Douan *et al.* (2020), Ghouri and McFarlane (1958), Kvassay (2014), Lachenicht *et al.* (2010), Lundy and Parrella (2015), Morales-Ramos *et al.* (2018), Patton (1978), Roe *et al.* (1980, 1985), Tregenza and Wedell (1997).
Humidity (% RH)	Incubating 90–100%, nursery period 70–80%, from 15 days on and for an adult 50–55% or 20–40%.	High humidity may be detrimental to later instars (older than the 4th) and adults.	Attard (2013), Clifford *et al.* (1977), Clifford and Woodring (1990), Ghouri and McFarlane (1958), Roe *et al.* (1980).
Growth	Pinhead, first instar/nymphal stage ≤0.32 cm, adult, mature 2.5 cm. The optimal age to harvest based on food consumption and biomass gain ratios was at the end of 8 weeks at 27 °C and at the end of 6 weeks at 29 °C. At 27 °C adults were significantly larger than at 29 °C.		Attard (2013), Morales-Ramos *et al.* (2018).
Mortality	Low < 6%, normal 10-20 %, high mortality >78 %.	'Mating effect' and a 'group effect', can affect the longevity patterns.	Collavo *et al.* (2005), Ghouri and McFarlane (1958), Morales-Ramos *et al.* (2018), Nowosielski and Patton (1965), Oonincx *et al.* (2015), Sorjonen *et al.* (2019), Vaga *et al.* (2021), von Hackewitz (2020).
Feed			
Feed intake	At 27 °C 5.5–321 and at 29 °C 6.7–266 mg dry-weight consumed/cricket/week from week 1 to 10. Adult female 70–86 mg/day (mated), 14–78 mg/day (virgin).	The mean amount of feed consumed by an adult at 30°C was 34 mg feed per day during the first 10 days of maturity. Nymphs consumed 16 to	Clifford and Woodring (1990), Morales-Ramos *et al.* (2018).

		28 mg/d throughout the penultimate and last instar, respectively.	
Particle size	Optimal particle size is comparable to crickets' size (≤ 1 mm dia, size from 0.212 to 1.0mm), hammer mill, 2mm mesh size. Finely ground feed for nympfs.		Attard (2013), Cohen (2015), Finke *et al.* (2005), Straub *et al.* (2019), Tennis *et al.* (1979).
Feed composition			
Macronutrients	Optimal feed contains 20–30% protein, 32–47% carbohydrates, and 3.2–5.2% fat. In the first 14-day period high-protein content is preferable, from 15 to 30 day protein content can be reduced to 14 %.	Commercial feeds typically have 14 to 21 % crude protein content.	Córdoba-Aguilar *et al.* (2016), Patton (1967), McFarlane (1964), Nakagaki and DeFoliart (1991), Neville *et al.* (1961), Hanboonsong and Durst (2020), Bawa *et al.* (2020).
Micronutrients	Thiamine (B1), pyridoxine (B6), nicotinic acid (B3), pantothenic acid (B5), choline and biotin (B7) are essential, the absence of riboflavin (B2), inositol (B8) or folic acid (B9) retard growth substantially. Vitamins C, E, K, sterol, manganese, some other minerals and trace elements.	Vitamin C, sterols, manganese, vitamins B1, B5 are the most important.	Ghouri and McFarlane (1958), Meikle (1964), McFarlane (1972abc, 1976a, 1978, 1991), McFarlane *et al.* (1959), Morales-Ramos *et al.* (2020), Neville *et al.* (1961), Ritchot (1960), Ritchot and McFarlane (1961), Visanuvimol and Bertram (2011).

3.1.8 Humidity

Relative humidity has diverse effects on different physiological processes of insects such as desiccation, weight loss of eggs, young nymphs, and adults (Clifford *et al.*, 1977; Holmes, 2010) and increased or decreased lifespan (Holmes, 2010; Tomberlin and Sheppard, 2002). Incubated eggs and young crickets need high humidity to survive as opposed to older crickets which require lower humidity (Clifford *et al.*, 1977; Clifford and Woodring, 1990; Table 5). Humidity can be increased in the cages by spreading water-soaked sponge or wet sand at the bottom of the cage.

3.1.9 Feed

Acheta domesticus belong to the Orthoptera order, and they have mandible mouthparts to tear off feed plant material (Cloutier, 2015). The hardness of the feed granule and the particle size of the feed should be such as to suit the mouthparts and eating behavior of each insect species (Panizzi and Parra, 2012). Crickets carry food particles on their body and mouthparts to the water if it is possible and they kick food out of the food dishes during feeding (Clifford and Woodring, 1990). Food consumption and growth occurs during the growth phase of the instar, which occurs between the molts (Ghouri and McFarlane, 1958; Woodring, 1983). Crickets begin feeding about 6 hours after molting and continue until mid-instar. After they reach mid instar phase and adequate size, they stop feeding and the moulting process begins (Woodring, 1983).

According to Finke (2015), soluble supplements may be suspended in a liquid and sprayed on the insect diet. Both adult and nymph crickets can consume also gel cubes and liquids. Reduced intake of feed in crickets has been reported if access to light, shelter, or water is restricted (Livingston *et al.*, 2014).

House cricket is omnivore, so it can eat a wide range of food sources, which can derive from animals and plants. In nature, house cricket eats leaves, seeds, fruits, and vegetables. In general, crickets prefer feed on plants, but they can eat other insects and even their own eggs if food or water is scarce or imbalanced (Cloutier, 2015; Simpson *et al.*, 2006). To successfully farm crickets, feed should be close to their natural diet (Hanboonsong *et al.*, 2013) and its optimal composition and particle size depends on the growth stage of the cricket (Table 5). Nonetheless, the house cricket has some preferences for certain ingredients over others, depending on available choices (Morales-Ramos *et al.*, 2020). Intake of vitamin C, sterol, manganese, and vitamins B1 and B5 had the most significant impact on live biomass production.

The use of plant-based by-products in diets for cricket mass-rearing is very encouraged, given that it represents an environmentally friendly feeding strategy (Oloo *et al.*, 2020; Oonincx *et al.*, 2015; Sorjonen *et al.*, 2019; Straub *et al.*, 2019). Weeds and agricultural by-products or flowering plants can also be used as feed (Miech, 2018; Morales-Ramos *et al.*, 2020; Vaga *et al.*, 2021). Small feed producer in Thailand combines rice bran with beer yeast (a waste product of beer factories), thus obtaining a high protein feed for crickets (Reverberi, 2020). On the other hand, municipal food waste, vegetable or green garden waste or manure used as feed can hamper growth or cause high mortality rate in crickets (Harsányi *et al.*, 2020; Lundy and Parrella, 2015).

Vegetables from the market or other sources might be contaminated by insecticides, so they should be washed thoroughly before being fed to crickets. Uneaten green vegetables should be removed from the rearing pens completely and replaced daily with fresh green plant material (Hanboonsong and Durst, 2020).

3.1.10 Water

The need for water is affected by the age of the insect, the quality of the feed, the temperature, the state of health, the stress, and the salinity of the feed (Panizzi and Parra, 2012). Water must be daily provided to crickets to avoid dehydration and water stress, as metabolic water production is usually insufficient to balance losses (Addo-Bediako *et al.*, 2001). Moderate water deprivation may drastically affect the life cycle duration and physiological parameters of the house cricket (Clifford *et al.*, 1977; McCluney and Date, 2008).

To reduce the chance of desiccation, fresh, free-standing water had to be always available to the crickets (Clifford *et al.*, 1977; Cloutier 2015). Water dispensers used on cricket farms are usually adapted from the commercial self-feeding type used in the poultry industry. Water can be dispensed through PVC pipes with sealed ends to store the water. A slit cut along the length of the pipe holds a cloth 'wick' that draws water out of the pipe as the crickets consume it (Hanboonsong and Durst, 2020). The number of water dispensers can be adjusted, with about one water dispenser per square meter of pen space (Hanboonsong and Durst, 2020).

The water dispensers should have sponges, cotton wool, small stones, or cloth mats in the feeding tray during the early growth of the crickets to prevent the young crickets from drowning (Hanboonsong and Durst 2020). The cloth mats or sponges used with water feeders are very high-risk reservoirs of harmful microbes, so frequent replacement and cleaning is essential. The water source must be always filled, and water replaced at least every three days (Hanboonsong and Durst, 2020; Kinyuru and Kipkoech, 2018).

Some cricket farmers use water crystals or polyacrylamide crystals as a water source (Kvassay, 2014; Morales-Ramos *et al.*, 2020). Crickets can be provided with water also by spraying on the surfaces of the container (Cloutier, 2015). However, if too much water is sprayed, feed can become excessively damp and/or being contaminated by fungi and other microbes (Hanboonsong and Durst, 2020). Crickets may get water also from fresh food such as cabbage, cucumber, carrot, potato, salad, or fruit (Ortiz *et al.*, 2016).

3.1.11 Rearing containers

A good container must serve the target insect's needs, including thermal features, humidity accommodation, gas exchange, being hospitable to developmental and reproductive needs, and any other microhabitat factors inherent in the insect's biology (Cohen, 2018). The rearing containers must meet the O_2 and CO_2 requirements of rearing insect species. Air must be circulated to avoid undesired air stratification, proliferation of fungi, bacteria or viruses, and the accumulation of CO_2 and other dangerous gases that can have detrimental effects on the health of the insect colony and workers (Cadinu *et al.*, 2020). The patterns of oxygen consumption measured by Booth and Kiddell (2007) were similar between 25 and 28 °C and reflected the growth patterns, as the first seven instars grew steadily, while a rapid increase in growth occurred during the last instar.

The house cricket jumps, so the sidewalls of the container should be at least 40 cm high. Crickets cannot climb smooth surfaces such as glass, plastic, metal, or aluminum foil. Providing hideouts (blinds) within the container for crickets is essential, because blinds give the crickets protection, extra space, and comfortable habitat where they can grow and shed their exoskeletons during molting. Common practice is to use commercial cardboard egg cartons stacked together for the blind, but also toilet paper rolls, crumpled newspaper and cardboard box dividers can also be used (Cloutier 2015;

Hanboonsong and Durst ,2020). Feed is best provided to crickets in shallow trays or bowls. The feed trays or plates are usually placed on top of the cricket blinds (Ortiz *et al.*, 2016; Hanboonsong and Durst 2020).

3.1.12 Harvesting

House crickets can be harvested as the final instar or as adults (Cloutier, 2015). Crickets are commonly harvested before they develop wings, thus as last instars. The first stage of harvesting involves the removal of feed trays and water sources from the rearing container. Crickets hide in the egg cartons, so the best way to collect adult crickets for harvesting is by tapping those cartons into a basin or bucket (Hanboonsong and Durst, 2020). In automated containers harvesting system includes semiautomated harvesting solutions (Entocube, 2021). Once harvested, it is recommended to cool the crickets by placing them in the freezer. Usually, crickets are killed by freezing at $^{-}$20 °C for 48 h (Kinyuru and Kipkoech, 2018). Processing and packaging facilities should be separated from rearing facilities (Hanboonsong and Durst, 2020).

3.2 Mathematical models and computer programs

Model-driven support system (MDSS) is a useful tool to help insect farmers make economically sensible decisions (Power, 2002). The models use data on insects' life cycle, ecology, bionomics, and performance on different substrates (Otieno *et al.*, 2019). The data produced by printed sensors, robots and an automated DSS (humidity, temperature, light, O_2 and CO_2, NH_3, vibration, sound, image, amount of feed and water consumed by crickets) can be integrated into the model (Baldini *et al.*, 2022; Kaklauskas, 2015; Wenning *et al.*, 2022). Models can provide recommendations to repetitive management problems based on fixed action rules and workflows. The program provides easily interpretable information for the insect farmer to help make the right decisions in managing insect rearing and assist in determining the time optimal rearing time. Adjusting production conditions optimal for each growth phase ensures insect well-being, best performance and of consistent quality cricket production, bringing the best economic output to the insect producer.

Mathematical models describing the relationship between insect reproduction and external factors have been developed since the 1920s (Janisch, 1925; Kaufmann, 1932; Eubank *et al.*, 1973; Sharpe and DeMichele, 1977). Janisch (1925) described the relationship between the developmental velocity (embryonic and larval) of an insect and environmental temperature with the help of a specific function. To better understand the effect of oscillating temperatures on insects, Kaufmann (1932) introduced the concept of summative temperatures, which is based on the product of developmental time and effective temperature (= environmental temperature – lower threshold temperature). An alternative to Kaufmann's concept is given by the mathematical technique of summative developmental rates (Ghouri and McFarlane, 1958; Eubank *et al.*, 1973), which also considers the rising complexity of insect development under rapidly fluctuating temperatures.

Insect growth modelling helps to obtain a better understanding of the life cycles of insects, which is very important for effective rearing of insects for food or feed. Sturm (2016a) introduced a simplified mathematical approach that describes the progression of larval growth in two hemimetabolous insects; *Teleogryllus commodus* and *A. domesticus*. The model is found on a distinction between hormonal growth rate and intrinsic growth rate, the latter of which includes the increase of larval size due to food consumption. In addition, any dependence of these growth rates on environmental temperature is considered. Evaluation of model validity was conducted by using experimental growth data that were determined for larvae of these two cricket species (Sturm, 2016a).

Sturm (2016b) introduced the computer program Crickthe rm, which aids to evaluate effect of various environmental factors on the daily fecundity of *A. domesticus*. The model of this computer program allows estimating the influence of environmental temperature, photoperiod, food composition, and population density on female oviposition. Model validation was conducted by comparing hypothetical and experimental fecundity data obtained for different constant temperatures (20, 27 and 34 °C) (Sturm, 2016b). The model provides a useful concept that can act as a starting point for further modelling work.

3.3 Emissions and frass

The rearing of crickets as mini livestock is considered more eco-friendly because of their low emission of greenhouse gases, low water and feed intake, and the small land requirement for their production as compared to conventional livestock (van Huis *et al.*, 2013; Oonincx *et al.*, 2015; Orinda, 2018; Bawa *et al.*, 2020). According to Oonincx *et al.* (2010) house crickets produce CO_2 68.0 g, 0.00 g CH_4, 0.1 mg N_2O, and 5.4 mg NH_3 per kilogram of bodymass per day. Per the kilogram of mass gain house crickets produce 0.0 g CH_4, 5.3 mg N_2O mg, 1.468 g CO_2 and 142.0 mg NH_3 in a day (28 °C, 70% RH).

Moreover, crickets may be produced on locally available food substrates such as agro-byproducts and weeds (Miech *et al.*, 2016; Orinda 2018; Magara *et al.*, 2019). Low temperature industrial surplus heat is also suitable for cricket farming (Reyes-Lúa *et al.*, 2021). In the northern regions, an old active disused mine may also operate as an ecological farming environment for crickets, taking advantage of the 28 °C geothermal heat (https://sifted.eu/articles/entocube-insect-farm-mine/).

House cricket farming produces waste (frass), which contains cricket feces, uneaten food, dead crickets, and shed exoskeletons. Frass production by *A. domesticus* equals 33–35 % of the feed consumed (McFarlane and Distler, 1982; Halloran *et al.*, 2017). Recycling the frass into a soil amending material can address the environmental risks and meet targets of the circular economy.

Cricket frass is rich in plant nutrients and likely promptly used as a soil amendment. Halloran *et al.* (2017) reported that the frass of house cricket contained 2.27% N, 2.02% P, and 2.26% K. According to Bukari *et al.* (2021) N content of cricket frass is higher 3.73%. These elements are higher than those of chicken manure (Halloran *et al.*, 2017). The results of the studies of Butnan and Duangpukdee (2021) and Bukari *et al.* (2021) show that cricket frass is a high-quality organic fertilizer for vegetable production. Cricket frass may enhance growth via increasing nutrient availability, alleviating elemental phytotoxicities, and promoting plant growth by hormone-like molecules (Butnan and Duangpukdee, 2021). If frass is used as fertilizer, the accumulation of heavy metals (arsenic, lead, cadmium, antimony, mercury) to the frass should be analyzed (Bukari *et al.*, 2021).

3.4 Quality and risk profile

The risk of contracting zoonotic diseases from some cricket species must also be taken into consideration (EFSA, 2015; Baiano 2020). The intestinal flora of crickets could be a predisposing agent for the growth of unwanted microorganisms (de Miranda *et al.*, 2021). Klunder *et al.* (2012) evaluated the microbial content of fresh, processed, and stored edible house crickets. The results showed that various types of Enterobacteriaceae and sporulating bacteria can be identified and subsequently separated from raw crickets entering them most likely during contact with the soil (Reineke *et al.*, 2012). According to Inácio *et al.* (2021) starvation (0–48 h) is not an effective method for reducing microbial loads in edible crickets.

The study of Fernandez-Cassi *et al.* (2019) assesses general processing steps and the risk profile of *A. domesticus* reared in closed systems. According to this study, the main hazards are: 1) high total counts of aerobic bacteria, 2) presence of spore-forming bacteria post thermal processing, 3) accumulation of cadmium and other heavy metals and 4) a possible increase of allergenic reactions due to exposure to insects and insect derived products. Eating crickets can also cause allergies to those persons sensitive to insect chitins (EFSA, 2015).

3.5 Costs and markets

Table 6 summarizes operational production costs and selling prices of *A. domesticus*, reported in selected studies. The production costs of insects are often quite high because of high labour costs, as routine procedures such as feeding are carried out manually. For example, Wouters *et al.* (2019) presented a model where labor costs were 62% of the total production costs. According to Morales-Ramos *et al.* (2018), house cricket reared at 27 °C resulted in a slightly higher profits per g of hatchling per year when compared to rearing at 29 °C (Morales-Ramos *et al.*, 2018).

The selling prices of house cricket products on the market vary greatly. An internet search performed in May and June 2022 indicated that some Asian suppliers can deliver wholesale quantities of *A. domesticus* meal at prices below three euros per kilogram fresh weight (price at the supplier).

The costs of rearing house cricket include the costs of labor input, feed and fresh vegetables (if supplied), energy, water, materials and equipment, housing, logistics and various supplies. Labor input is a substantial cost in small-scale production. Techno-economic analysis conducted by using the costing calculation of Niemi *et al.* (2020) as a starting point suggests that if automation could reduce the use of labor input by 75%, as found by Wouters *et al.* (2019) for mealworm, the production costs per kilogram of house cricket could decrease by 38–55% (Figure 4). Besides feed conversion ratio, feed quality and feed price, other economically critical parameters which appropriate level must be ensured, include mortality, and temperature which can lead to substantial mortality if 35 °C, is exceeded. The incubation time efficiency and rearing efficiency during nursery period are also important parameters as they are influenced substantially by temperature, humidity, and diet quality.

Table 6. Prices of house cricket products and operational costs of rearing as presented in scientific literature (table modified from Niyonsaba et al., 2021; Niemi et al., 2020).

Country	Price, €/t	Product type	Operational cost, €/t dried larvae	Reference
Thailand	1,867-3,952/26,363	Fresh/Meal	na	Halloran *et al.* (2016)
Thailand	2,018-2,950	Fresh	na	Halloran *et al.* (2017)
Thailand	2,363-3,272	Fresh	na	Hanboonsong *et al.* (2013)
USA	84,590	Meal	5,914 (feed)	MoralesRamos *et al.* (2020)
USA	30,000-36,346	Meal	na	Reverberi (2020)
Canada	18,182	Meal	na	Reverberi (2020)
Belgium	45,455	Dried	na	Reverberi (2020)
The Netherlands	200,000	Dried	na	Meuwissen (2011)
China/Finland	6,000-38,000	Meal	30,000- 81,510*	Niemi *et al.* (2020)

*Includes the total production costs. na means information not available.

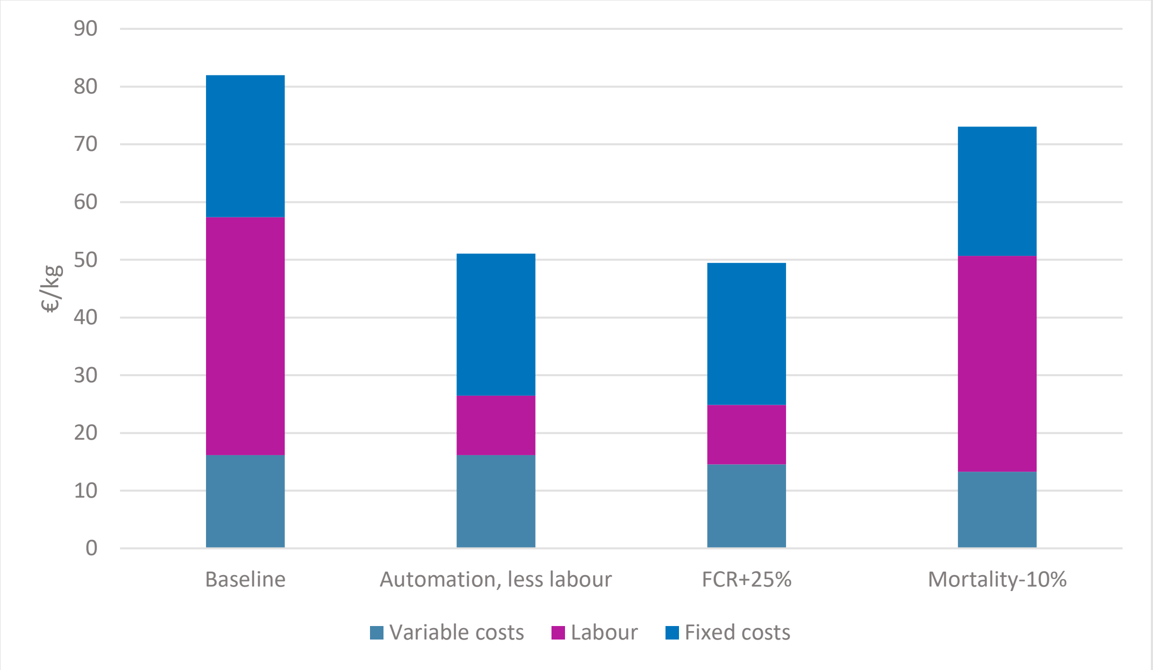


Figure 4. Four scenarios describing the effect of automation, improved feed conversion ratio (FCR) and reduced mortality on the production costs of house cricket (scenarios derived by using the results of Niemi et al., 2020).

3.6 Concluding remarks

The nutrition and the rearing environments of house crickets is to some extent different from two other species considered in this deliverable. Key performance indicators for house cricket include parameters such as growth rate, feed conversion ratio and mortality. Because feed quality can have a major impact on these parameters, it is essential to have information also about feed's nutritional content. Feed should contain sufficient amounts of amino acids, vitamin C, sterol, manganese, and vitamins B1 and B5, as these impact live biomass production. In addition to feed, house crickets must be supplied also water either as such or by using fresh vegetables. As the source of water can quickly be contaminated with molds or bacteria, its quality should be monitored daily, replenished regularly and not be supplied in large quantities. Because labor and fixed inputs are major inputs in terms of their contribution to the costs, some of the key factors to make the products more cost-competitive are to increase the growth rates, reduce mortality, and to increase the size and automation level of the facility.

Similar to BSF, also house crickets' production performance can vary substantially and fairly small deviations from the desirable rearing environment parameters can result is substantial changes on production performance. Optimizing rearing conditions for house crickets increases the production efficiency and improves the well-being of the animals. Rearing conditions are expected to simulate the natural environments from which target insects are derived Conditions such as temperature, light-dark cycle, humidity, and available space influence the insect development. Temperature is the most important abiotic factor influencing the biology of insects. A few degrees too high or too low temperatures can already reduce the growth substantially. For house crickets, the temperature of the rearing environment should be very close to 29°C. High humidity can increase the risks of pathogen infections, which may compromise the viability of cricket population. Rearing facilities should provide suitable conditions to allow insects to perform the reproductive functions that allow them to sustain continuous generations of offspring. These conditions include mating accommodations, suitable oviposition circumstances, and appropriate hatching and developmental requirements. Overall, modelling approaches has been found useful analyzing different practices that can be used to manage house cricket rearing process.

3.7 References

Addo-Bediako, A., Chown S. L., Gaston K. J. 2001. Revisiting water loss in insects: a large scale view. J. Insect Physiol. 47, 1377–1388.

Baldini, G., Albini A., Maiolino, P., Cannata, G. 2022. An Atlas for the Inkjet Printing of Large-Area Tactile Sensors. Sensors 22, 2332. https://doi.org/10.3390/s22062332.

Baiano, A. 2020. Edible insects: an overview on nutritional characteristics, safety, farming, production technologies, regulatory framework, and socio-economic and ethical implications. Trends in Food Science & Technology 100, 35-50. https://doi.org/10.1016/j.tifs.2020.03.040.

Bawa, M., Songsermpong, S., Kaewtapee, C., Chanput, W. 2020. Effect of Diet on the Growth Performance, Feed Conversion, and Nutrient Content of the House Cricket Journal of Insect Science, 20(2), 10,1–10.

Booth, D.T., Kiddell, K. 2007. Temperature and the energetics of development in the house cricket (*Acheta domesticus*). J Insect Phys 53, 950–953.

Bukari, N.I., Ghani, I.A, Mustaffa, M., Harun, A., Abdullah, H.A., Abdullah, H.S., Basir, S., Yusop, R.M., Muzamil, M.F.M. 2021. The Effect of Cricket (Orthoptera: Gryllidae) Frass on the Growth of Leafy Vegetables. ASM Sc. J., 14, Special Issue 1, 2021 for ICSTSS2018, 175–181.

Busvine, J.R. 1955. Simple methods for rearing the cricket (*Gryllulus domesticus* L.) with some observations on speed of development at different temperatures. Proceedings of Royal Entomological Society of London 30, 15–18.

Butnan, S., Duangpukdee J. 2021. Cricket frass: The high-quality organic fertilizer for vegetable growth improvement. Khon Kaen Agriculture Journal Suppl. 1.

Cadinu, L.A., Barra, P., Torre, F., Delogu, F., Madau, F.A. 2020. Insect Rearing: Potential, Challenges, and Circularity. Sustainability 12, 4567.

Clifford, C.W., Woodring, J. 1990. Methods for rearing the house cricket, *Acheta domesticus* (L.), along with baseline values for feeding rates, growth rates, development times, and blood composition. Journal of Applied Entomology 109 (1-5), 1–14.

Clifford, W., Roe, R.M., Woodring, J.P. 1977. Rearing methods for obtaining house crickets Acbetu domesticus of known age, sex and instar. Annals of the Entomological Society of America 70 (l), 69– 74.

Cloutier, J. 2015. Edible insects in Africa: An introduction to finding, using and eating insects. Agrodok 54. Agromisa Foundation and CTA, Wageningen. 80 s. ISBN 978-90-8573-146-7.

Cohen, A.C. 2015. Insect Diets: Science and Technology. 2nd Edition, CRC Press. Boca Raton, FL.

Cohen, A.C. 2018. Ecology of Insect Rearing Systems: A Mini-Review of Insect Rearing Papers from 1906-2017. Advances in Entomology, 6, 86-115. https://doi.org/10.4236/ae.2018.62008.

Collavo, A. Glew, R.H. Huang, Y.-S. Chuang, L.-T. Bosse, R., Paoletti, M.G. 2005. House cricket small-scale farming. In: Paoletti, M.G. (ed.) Ecological implications of minilivestock. Science Publishers, Inc., Enfield. pp. 515–540.

Córdoba-Aguilar, A., A. Nava-Sánchez, D. M. González-Tokman, R. Munguía-Steyer, A. E. Gutiérrez-Cabrera. 2016. Immune Priming, Fat Reserves, Muscle Mass and Body Weight of the House Cricket is Affected by Diet Composition. Neotropical Entomology. https://doi.org/10.1007/s13744-016-0391-0.

Cymborowski, B. 1973. Control of the circadian rhythms of locomotor activity in the house cricket. Journal of Insect Physiology 19, 1423–1440.

de Miranda, J.R., Granberg, F., Low, M., Onorati, P., Semberg, E., Jansson, A., Berggren, Å. 2021. Virus Diversity and Loads in Crickets Reared for Feed: Implications for Husbandry. Front. Vet. Sci. 8, 642085. doi: 10.3389/fvets.2021.642085.

Douan, B.G., Doumbia, M., Kwadjo, K.E., Kra, K.D. 2020. Morphological description of the house cricket (*Acheta domesticus* Linnaeus, 1758; Orthoptera: Gryllidae) egg in captivity. Int J Trop Insect Sci. https://doi.org/10.1007/s42690-020-00338-x.

EFSA Scientific Committee. 2015. Risk profile related to production and consumption of insects as food and feed. EFSA J. 13,4257. doi: 10.2903/j.efsa.2015.4257.

Entocube. 2021. available online: https://entocube.com/wp-content/uploads/2021/07/EntoCube-10X-brochure-v2.pdf.

Eubank, W.P., Atmar, J.W., Ellington, J.J. 1973. The significance and thermodynamics of fluctuating versus static thermal environments in *Heliothis zea* egg development rates. Environmental Entomology, 2,491–496. (only abst.).

Fernandez-Cassi, X., Supeanu, A., Vaga, M., Jansson, A., Boqvist, S., Vagsholm, I. 2019. The house cricket (*Acheta domesticus*) as a novel food: a risk profile. Journal of Insects as Food and Feed, 5(2), 137–157.

Finke, M.D., Oonincx, D. 2014. Insects as food for insectivores. In: Morales-Ramos, J.A., Guadalupe Rojas, M., Shapiro-Ilan, D.I. (Eds.) Mass Production of Beneficial Organisms: Invertebrates and Entomopathogens (pp. 583-616). New York, NY: Academic Press. https://doi.org/10.1016/B978-0-12-391453-8.00017-0.

Ghouri, A.S.K., McFarlane, J.E. 1958. Observations on the development of crickets. The Canadian Entomologist 90, 158–165.

Górska-Andrzejak, J., Wojtusiak, J. 2003. Comparative study of the level of locomotor activity throughout postembryonic development of two cricket species: *Acheta domesticus* L. and Gryllus bimaculatus De Geer (Ensifera: Gryllidae). Journal of Insect Behavior 16, 845–857.

Halloran, A., Roos, N., Flore, R., Hanboonsong, Y., 2016. The development of the edible cricket industry in Thailand. Journal of Insects as Food and Feed 2, 91-100. https://doi.org/10.3920/

Halloran, A., Hanboongsong, Y., Roos, Y., Bruun, S. 2017. Life cycle assessment of cricket farming in north-eastern Thailand. Journal of Cleaner Production 156, 83–94. Available online: https://doi.org/10.1016/j.jclepro.2017.04.017.

Halloran, A., Roos, N., Hanboonsong, Y., 2017. Cricket farming as a livelihood strategy in Thailand. The Geographical Journal 183, 112-124. https://doi.org/10.1111/geoj.12184

Hanboonsong, Y., Durst, P.B. 2014. Edible insects in Lao PDR: Building on tradition to enhance food security. RAP Publication 2014/12. Regional Office of Asia and the Pacific of the Food and Agricultural Organization, UN, Bangkok. 56 p. Available online: http://www.fao.org/3/a-i3749e.pdf.

Hanboonsong, Y., Durst, P.B. 2020. Guidance on sustainable cricket farming – A practical manual for farmers and inspectors. Bangkok. Available online: https://doi.org/10.4060/cb2446en.

Hanboonsong, Y., Jamjanya, T., Durst, P.B. 2013. Six-legged livestock, edible insect farming, collecting and marketing in Thailand. Regional Office of Asia and the Pacific of the Food and Agricultural Organization, UN, Bangkok. 69 p. Available online: http://www.fao.org/docrep/017/i3246e/i3246e.pdf.

Harsányi, E., Juhász, C., Kovács, E., Huzsvai, L., Pintér, R., Fekete, G., Varga, Z.I., Aleksza, L., Gyuricza, C. 2020. Evaluation of Organic Wastes as Substrates for Rearing Zophobas morio, Tenebrio molitor, and *Acheta domesticus* Larvae as Alternative Feed Supplements. Insects 11, 1–17, doi:10.3390/insects11090604.

Huber, F. 1962. Central nervous control of sound production in crickets and some speculations on its evolution. Evolution, 16,429—442.

Inácio, A.C., Vågsholm, I., Jansson, A. Vaga, M., Boqvist, S., Fraqueza, M.J. 2021. Impact of starvation on fat content and microbial load in edible crickets (*Acheta domesticus*). Journal of Insects as Food and Feed (article in press).

Janisch, F. 1925. Über die Temperaturabhängigkeit biologischer Vorgänge und ihre kurvenmäßige Erfassung. Pflügers Archiv, 209:414–436.

Kaklauskas, A. 2015. Intelligent Decision Support Systems. 10.1007/978-3-319-13659-2_2.

Kaufmann, O. 1932. Einige bemerkungen über den einfluss von temperaturschwankungen auf die entwicklungsdauer und streuung bei insekten und seine graphische darstellung durch kettenlinie und hyperbel. Zeitschrift für Morphologie und Ökologie der Tiere, 25,354–361.

Kinyuru, J.N., Kipkoech, C., 2018. Production and growth parameters of edible crickets: experiences from a farm in a high altitude, cooler region of Kenya. Journal of Insects as Food and Feed 4, 247–251. Available online: https://doi.org/10.3920/JIFF2017.0081.

Klunder, H.C., Wolkers-Rooijackers, J., Korpela, J.M., Nout, M.J.R. 2012. Microbiological aspects of processing and storage of edible insects. Food Control. 26, 628–31. doi: 10.1016/j.foodcont.2012.02.013.

Kvassay, G., 2014.The complete cricket breeding manual. 3. edition. CreateSpace Independent Publishing Platform, Scotts Valley. 164 s.

Lachenicht, M.W. Clusella-Trullas, S. Boardman, L., Le Roux C., Terblanche, J.S. 2010. Effects of acclimatation temperature on thermal tolerance, locomotion performance and respiratory metabolism in *Acheta domesticus* L. (Orthoptera: Gryllidae). Journal of Insect Physiology 56, 822-830.

Liu, S.S., Zhang, G.M., Zhu, J., 1995. Influence of temperature variations on rate of development in insects: analysis of case studies from entomological literature. Annals of the Entomological Society of America 88, 107–119.

Livingston, S., Lavin, S.R., Sullivan, K., Attard, L., Valdes, E.V. 2014. Challenges with effective nutrient supplementation for amphibians: a review of cricket studies. Zoo Biology 33, 565–576.

Lundy, M.E., Parrella, M.P. 2015. Crickets are not a free lunch: Protein capture from scalable organic side-streams via high-density populations of *Acheta domesticus*. PLOS ONE 10(4): e0118785. doi:10.1371/journal.pone.011878511 pmid:25875026.

Magara, J.O.H., Tanga, C.M., Ayieko, M. A., Hugel, S., Samira, A. M., Khamis, F.M., Salifu, D., Niassy, S., Subramanian, S., Komi, K.M.F, Roos, N., Ekesi, S. 2019. Performance of Newly Described Native Edible Cricket Scapsipedus icipe (Orthoptera: Gryllidae) on Various Diets of Relevance for Farming. Journal of Economic Entomology 112, 653-664. doi: 10.1093/jee/toy397.

McCluney. K.E., Date. R.C. 2008. The effects of hydration on growth of the house cricket, *Acheta domesticus*. Journal of Insect Science 8, 1–9.

McFarlane. J.E. 1972a. Vitamin E, tocopherol quinone and selenium in the diet of the house cricket, *Acheta domesticus* (L.). Israel Journal of Entomology 7, 7–14.

McFarlane. J.E. 1972b. Studies on vitamin E in the house cricket, *Acheta domesticus* (L.) (Orthoptera: Gryllidae). I. Nutritional albinism. The Canadian Entomologist 104, 511–514.

McFarlane, J.E. 1972c. Studies on vitamin E in the house cricket, *Acheta domesticus* (L.) (Orthoptera: Gryllidae) II. In vivo inhibition by vitamin E of a phenolase system in the egg. The Canadian Entomologist 104, 515–518.

McFarlane, J.E. 1976a. Influence of dietary copper and zinc on growth and reproduction of the house cricket (Orthoptera: Gryllidae). The Canadian Entomologist 108, 387–390.

McFarlane, J.E. 1976b. Vitamin K: a growth factor for the house cricket (Orthoptera: Gryllidae). The Canadian Entomologist 108, 391–394.

McFarlane, J.E. 1978. Vitamins E and K in relation to growth of the house cricket (Orthoptera: Gryllidae). The Canadian Entomologist 110, 329–330.

McFarlane, J.E. 1991. Dietary sodium, potassium and calcium requirements of the house cricket, *Acheta domesticus* (L.). Comparative Biochemistry & Physiology 100A, 217–220.

McFarlane, J.E. 1962. The larvae of the house cricket, *Acheta domesticus* (L.), grow more rapidly when reared in groups of 10 than when reared singly. Can. J. Zool. 40, 559–560.

McFarlane, J.E. 1964. The protein requirements of the house cricket, *Acheta domesticus* L. Canadian Journal of Zoology 42, 645–647.

McFarlane, J.E., Neilson, B., Ghouri, A.S.K. 1959. Artificial diets for the house crickets, *Acheta domesticus* (L.). Can. J. Zool. 37, 913– 916.

Meikle, J. 1964. The role of lipid in the nutrition of the house cricket, *Acheta domesticus* L. (Orthoptera: Gryllidae). A Thesis, McGill University.

Meuwissen, P., 2011. Insects as new protein source. A scenario exploration of market opportunities. Insecten als nieuwe eiwitbron. Een scenarioverkenning van de marktkansen. ZLTO, ’s Hertogenbosch, the Netherland

Miech, P. 2018. Cricket farming: an alternative for producing food and feed in Cambodia. Doctoral Thesis. Swedish University of Agricultural Sciences.

Miech, P., Berggren, Å., Lindberg, J.E., Chhay, T., Khieu, B., Jansson, A. 2016. Growth and survival of reared Cambodian field crickets (*Teleogryllus testaceus*) fed weeds, agricultural and food industry by-products. JIFF. 2, 285–92. doi: 10.3920/JIFF2016.0028.

Mirhosseini, M.A., Fathipour, Y., Reddy, G.V.P. 2017. Arthropod development’s response to temperature: a review and new software for modeling. Annals of the Entomological Society of America 110, 507–520.

Morales-Ramos, J.A., Rojas, M.G., Dossey, A.T. 2018. Age-dependent food utilization of *Acheta domesticus* (Orthoptera: Gryllidae) in small groups at two temperatures. J Ins Food Feed. 4, 51–60.

Morales-Ramos, J.A., Rojas, M.G., Dossey, A.T., Berhow, M. 2020. Self-selection of food ingredients and agricultural by-products by the house cricket, *Acheta domesticus* (Orthoptera: Gryllidae): A holistic approach to develop optimized diets. PLoS ONE 15(1), e0227400. Available online: https://doi.org/10.1371/journal.pone.0227400.

Nakagaki, B.J., DeFoliart, G.R. 1991. Comparison of diets for mass-rearing *Acheta domesticus* (Orthoptera: Gryllidae) as a novelty food, and the comparison of food conversion efficiency with values reported for livestock. Journal of Economic Entomology 84, 891–896.

Nelson, C.M., Nolen, T.G. 1997. Courtship song, male agonistic encounters, and female mate choice in the house cricket, *Acheta domesticus* (Orthoptera: Gryllidae). Journal of Insect Behavior, 10 (4), 557–570.

Neville, P.F., Stone, P.C, Luckey, T.D. 1961. Cricket Nutrition: II. An Unidentified Factor in the Nutrition of *Acheta Domesticus.* The Journal of Nutrition, Volume 74, Issue 3, July 1961, Pages 265–273.

Niemi, J.K., Karhapää, M., Mellberg, S., Latomäki, I., Wirtanen, G. 2020. Hyönteisten kasvatus ja käyttö ruokana tai rehuna. Luonnonvara- ja biotalouden tutkimus 49/2020. Luonnonvarakeskus. Helsinki. 114 p.

Nix, P.M., Bass, M.H. 1973. Biological and toxicological notes on the house cricket. Agricultural Experiment Station, Auburn University. Leaflet 86. 4 s.

Niyonsaba, H., Höhler, J. Kooistra, J., Van der Fels-Klerx, H, Meuwissen, M. 2021. Profitability of insect farms. Journal of Insects as Food and Feed 7, 923-934.

Nowosielski, J.W., Patton, R.L. 1963. Studies on circadian rhythm of the house cricket, *Gryllus domesticus* L. J. Insect Physiol. 9, 401–410.

Nowosielski, J.W., Patton, R.L. 1965. Life-tables for the house cricket, *Acheta domesticus* L., and the effect of Intra-specific factors on longevity. J. Ins. Physiol. 11, 201–209.

Oloo, J.A., Ayieko, M., Nyongesah, J.M. 2020. *Acheta domesticus* (Cricket) feed resources among smallholder farmers in Lake Victoria region of Kenya. Food Sci Nutr. 8, 69–78. https://doi.org/10.1002/fsn3.1242.

Oonincx, D.G.A.B., van Broekhoven, S., van Huis, A., van Loon J.J.A. 2015. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLOS ONE 10(12), e0144601. Available online: https://doi.org/10.1371/journal.pone.0144601.

Oonincx, D.G.A.B., Van Itterbeeck, J., Heetkamp, M.J.W., Van den Brand, H., Van Loon, J.J.A., Van Huis, A., 2010. An Exploration on Greenhouse Gas and Ammonia Production by Insect Species Suitable for Animal or Human Consumption. PLoS ONE 5, e14445. Available online: https://doi.org/10.1371/journal.pone.0014445.

Orinda, M.A. 2018. Effects of housing and feed on growth and technical efficiency of production of *Acheta domesticus* (L) and Gryllus bimaculatus for sustainable commercial crickets production in the lake victoria region, Kenya. (Doctoral dissertation, JOOST). Available online at: http://ir.jooust.ac.ke:8080/xmlui/handle/123456789/8852 (accessed on March 25, 2021).

Orinda, M., Oloo, J., Magara, H., Ayieko, M., Roo, N. 2020. Cricket Rearing Handbook. 10.14738/eb.86.2020.

Ortiz, J.A.C., Ruiz, A.T., Morales-Ramos, J.A., Thomas, M., Rojas, M.G., Tomberlin, J.K., Yi, L., Han, R., Giroud, L., Jullien, R.L. 2016. Chapter 6 - Insect mass production technologies. In: Dossey, A.T., Morales-Ramos, J.A., Rojas, M.G. (ed.) Insects as sustainable food ingredients. Academic Press, San Diego. s. 153–201. ISBN 9780128028568.

Otieno, M.H.J., Ayieko, M.A., Niassy, S., Salifu, D., Abdelmutalab, A.G.A, Fathiya, K.M., Subramanian, S., Fiaboe, K.K.M., Roos, N., Ekesi, S., Chrysantus, M. Tanga, C.M. 2019. Integrating temperature-dependent life table data into Insect Life Cycle Model for predicting the potential distribution of *Scapsipedus icipe* Hugel & Tanga. PLoS ONE 14(9), e0222941. Available online: https://doi.org/10.1371/journal.pone.0222941.

Panizzi, A.R., Parra, J.R.P. 2012. Insect bioecology and nutrition for integrated pest management. In: Panizzi, A.P., Parra, J.R.P. (ed.) Contemporary Topics in Entomology. CRC Press, Boca Raton.

Parajulee, M., DeFoliart, G., Hogg, D. 1993. Model for use in mass-production of *Acheta domesticus* (Orthopeda: Gryllidae) as Food. Journal of Economic Entomology, 86(5), pp. 1424–1428.

Patton, L. 1963. Rearing the house cricket, *Acbetu domesticus*, on commercial feed. Ann. Ent. Soc. Am. 56, 250–251.

Patton, R.L. 1967. Oligidic diets for *Acheta domesticus* (Orthoptera: Gryllidae). Annals of the Entomological Society of America 60, 1238–1242.

Patton, R.L. 1978. Growth and development parameters for *Acheta domesticus* (Orthoptera Gryllidae). Annals of the Entomological Society of America 71, 40–42.

Power, D.J. 2002. Decision Support Systems: Concepts and Resources for Managers. Faculty Book Gallery. 67.

Rebaudo, F., Rabhi, V.-B. 2018. Modeling temperature-dependent development rate and phenology in insects: review of major developments, challenges, and future directions. Entomol Exp Appl, 166, 607-617. https://doi.org/10.1111/eea.12693.

Reineke, K., Doehner, I., Schlumbach, K., Baier, D., Mathys, A., Knorr, D. 2012. The different pathways of spore germination and inactivation in dependence of pressure and temperature. Food Sci Emerg Technol. 13, 31–41. doi: 10.1016/j.ifset.2011.09.006.

Reverberi, M., 2020. Edible insects: cricket farming and processing as an emerging market. Journal of Insects as Food and Feed 6, 211–220.

Reyes-Lúa, A., Straus, J., Skjervold, V.T., Durakovic, G., Nordtvedt, T.S. 2021. A Novel Concept for Sustainable Food Production Utilizing Low Temperature Industrial Surplus Heat. Sustainability 13, 9786. https://doi.org/10.3390/su13179786.

Ritchot, C. 1960. The B vitamin requirements of the house cricket. Master thesis at the Faculty of Department of Entomology, McGill University, Montreal. 63 s.

Roe, R.M., Clifford, C.W., Woodring, J.P. 1980. The effect of temperature on feeding, growth, and metabolism during the last larval stadium of the female house cricket, *Acheta domesticus*. Journal of Insect Physiology 26, 639–644.

Roe, R.M., Clifford, C.W., Woodring, J.P. 1985. The effect of temperature on energy-distribution during the last-larval stadium of the female house cricket, *Acheta domesticus*. Journal of Insect Physiology 31, 371–378.

Rumpold, B.A., Schluter, O.K. 2013. Potential and challenges of insects as an innovative source for food and feed production. Innovative Food Science and Emerging Technologies 17, 1–11.

Sharpe, O. J. H., DeMichele D. W. 1977. Reaction kinetics of poikilotherm development. Journal of Theoretical Biology. 64, 649–670.

Simpson S.J., Sword G.A., Lorch P.D., Couzin I.D. 2006. Cannibal crickets on aforced march for protein and salt. Proc Natl Acad Sci USA 103, 4152–4156.

Sorjonen, J.M., Valtonen, A., Hirvisalo, E., Karhapää, M., Lehtovaara, V.J., Lindgren, J., Marnila, P., Mooney, P., Mäki, M., Siljander-Rasi, H., Tapio, M., Tuiskula-Haavisto, M., Roininen, H. 2019. The plant-based by-product diets for the mass-rearing of *Acheta domesticus* and Gryllus bimaculatus. PLOS ONE 14(6), e0218830. https://doi.org/10.1371/journal.pone.0218830. Insectes Sociaux 14, 415–426.

Straub, P., Tanga, C.M., Osuga, I., Windisch, W., Subramanian, S. 2019. Experimental feeding studies with crickets and locusts on the use of feed mixtures composed of storable feed materials commonly used in livestock production. Animal Feed Science and Technology 255, 114215. https://doi.org/10.1016/j.anifeedsci.2019.114215.

Sturm, R. 2016a. Modeling Larval Growth of Various Cricket Species (Insecta, Orthoptera). Journal of Computational Biology 5(6), 1–10.

Sturm, R. 2016b. Computer models in Entomology: Predicting the daily fecundity of female *Acheta domesticus*. — Comp. Math. Biol. 5, 3.

Sturm, R. 2017. Dependence of daily oviposition activity and total fecundity on body mass in the house cricket *Acheta domesticus* (L.) (Insecta: Orthoptera). — Linzer biol. Beitr. 49 (1), 961–969.

Tennis, P., Koonce, J., Teraguc, M. 1977. The effects of population density and food surface area on body weight of *Acheta domesticus* (L.) (Orthopeda: Gryllidae). Canadian Journal of Zoology, Volume 55, pp. 2004–2010.

Tregenza, T., Wedell, N. 1997. Definitive evidence for cuticular pheromones in a cricket. Animal Behavior 54, 979-984.

Vaga, M., Berggren, Å., Jansson, A. 2021. Growth, survival and development of house crickets (*Acheta domesticus*) fed flowering plants. Journal of Insects as Food and Feed 2021, Vol. 7, No. 2, pp. 151–161. Available online: https://doi.org/10.3920/JIFF2020.0048.

Van Huis, A. 2013. Potential of insects as food and feed in assuring food security. Annu. Rev. Entomol. 58, 563–583.

Van Huis, A., van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P. 2013. Edible insects: future prospects for food and feed security. FAO, Rome. E-ISBN 978-92-5-107596-8. 187 s.

Visanuvimol, L, Bertram, SM. 2011. How dietary phosphorus availability during development influences condition and life history traits of the cricket, *Acheta domesticus*. Journal of Insect Science 11, 63 available online: insectscience.org/11.63.

von Hackewitz, L. 2020. Sustainable and cost-efficient feed ingredients for optimum breeding of house crickets (*Acheta domesticus*) for human consumption in Thailand. Uppsala: SLU, Department of Molecular Sciences. Available online: https://stud.epsilon.slu.se/16670/.

Wenning, M.J., Piotrowski, T., Janzen, J., Nießing, B., Schmitt, R.H. 2022. Towards monitoring of a cricket production using instance segmentation. Journal of Insects as Food and Feed, 1-10 Wageningen Academic Publishers, ISSN 2352-4588 online, DOI 10.3920/JIFF2021.0165.

Wagner, T.L., Wu, H-I., Sharpe, P.J.H., Schoolfield, R.M., Coulson, R.N. 1984. Modeling Insect Development Rates: a Literature Review and Application of a Biophysical Model, Annals of the Entomological Society of America 77, 208–220. Available online: https://doi.org/10.1093/aesa/77.2.208.

Walker, T.J. 1962. Factors responsible for intraspecific variation in the calling songs of crickets. Evolution 16, 407–428.

Woodring, J.P., Roe, R.M., Clifford, C.W. 1977. Relation of feeding, growth, and metabolism to age in the larval, female house cricket. Journal of Insect Physiology 23(2), 207–212.

Woodring, J.P., Clifford, C.W. 1986. Development and relationships of locomotor, feeding, and oxygen consumption rhythms in house crickets. Physiological Entomology 11, 89–96.

Wouters, F., Schillewaert, S., Spranghers, T. 2020. Cost-effective insect rearing through automation and sidestream valorization. Abstract. Insecta 2020 conference.

4 Mealworm (*Tenebrio molitor* (Coleoptera: Tenebrionidae))

4.1 Bio-physical information on the rearing process

4.1.1 Basic information

The mealworm *T. molitor* Linnaeus (Coleoptera: Tenebrionidae) (Figure 5) is one of the most promising insects reared at an industrial scale as novel food source for humans (Morales-Ramos *et al.*, 2019). Mealworms are easy to rear under artificial conditions and are commonly fed with wheat bran with protein supplementation, while vegetables are provided as water source (Morales-Ramos *et al.*, 2013). Mealworms are efficient in transforming diet substrate with a low nutritional value in rich protein biomass (Van Huis *et al.*, 2013). Mealworms are suitable for human consumption and their nutritional value is comparable to that of beef and chicken (Li *et al.*, 2013; Truzzi *et al.*, 2019). However, diets and procedures used in small-scale rearing facilities barely meet the criteria for automated mass production at industrial levels (van Huis *et al.*, 2013).

Tenebrio molitor is a species belonging to the Tenebrionidae Family, commonly known as darkling beetles (adults) or mealworms (larvae). It undergoes a complete metamorphosis after four stages of development, namely egg, larvae, pupae, and adult (Figure 5). This cosmopolitan insect feeds primarily on farinaceous materials and is accordingly considered a pest in flour mills and barns (Ghaly and Alkoaik, 2009). A summary of the life cycle is presented in Table 7.

4.1.2 Eggs

The female lays an average of 400-500 eggs singly or in small clusters, attached to the substrate or the walls and floor of the containers where they are bred (Ghaly and Alkoaik, 2009; Selaledi *et al.*, 2020). After a period varying between 4 days at 26-30 ºC and 34 days at 15 ºC, the larvae emerge from the eggs (Kim *et al.*, 2015).

4.1.3 Larvae

The larval stage varies from 57 days in controlled conditions to 629 days in nature, even if the most common duration of this stage ranges from 112 to 203.3 days (Ghaly and Alkoaik, 2009). Shorter durations of the entire lifecycle of *T. molitor* have been reported by Spencer and Spencer (2006) and Hardouin and Mahoux (2003) with 75 and 90 days, respectively. During the larval stage, the larvae undergo several molts, varying from a minimum of 8 to a maximum of 23 (Ludwig, 1956), even if the most common number of instars ranges from 11 to 20 (Kim *et al.*, 2015).

4.1.4 Pupae

After the larval stage, the larvae undergo a short period of latency and assume a "C" shape before turning into a pupa, after which metamorphosis takes place. The pupa stage takes from 6 to 20 days (Ghaly and Alkoaik, 2009; Hill, 2002; Selaledi *et al.*, 2020).

4.1.5 Adults

Adults emerge as white beetles with a soft exoskeleton, which gradually darkens. Adults can start oviposition 3 days after emerging. The adult stage of *T. molitor* commonly lasts from 16 to 173 days, mostly from 31.8 to 62 days (Miryam *et al.*, 2000). The highest reproductive output is however at 2 and 3 weeks after emergence (Morales-Ramos *et al.*, 2012). In nature, the entire life cycle takes place in the same ecosystem and the duration of the different stages is highly dependent on environmental conditions. Similarly, temperature, relative humidity, diet, population density and sex-ratio of the population can strongly influence the development and growth of *T. molitor* in rearing facilities (Ortiz *et al.*, 2016, Zim *et al.*, 2022, Jehan *et al.*, 2020).

.

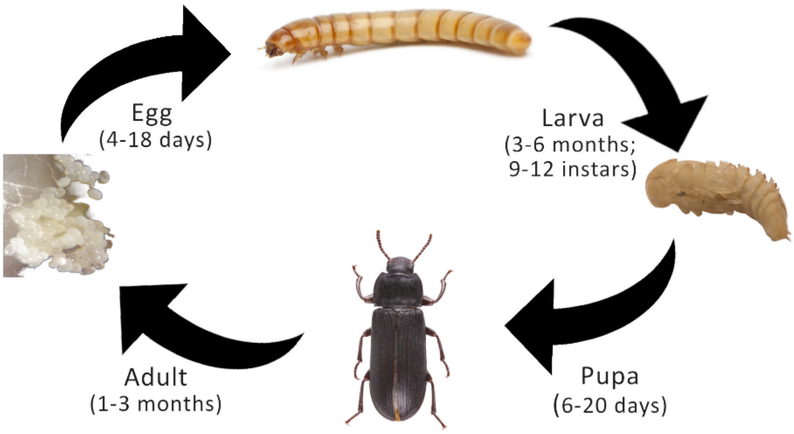


Figure 5. Life cycle of T. molitor.

4.1.6 Rearing density and cycle management

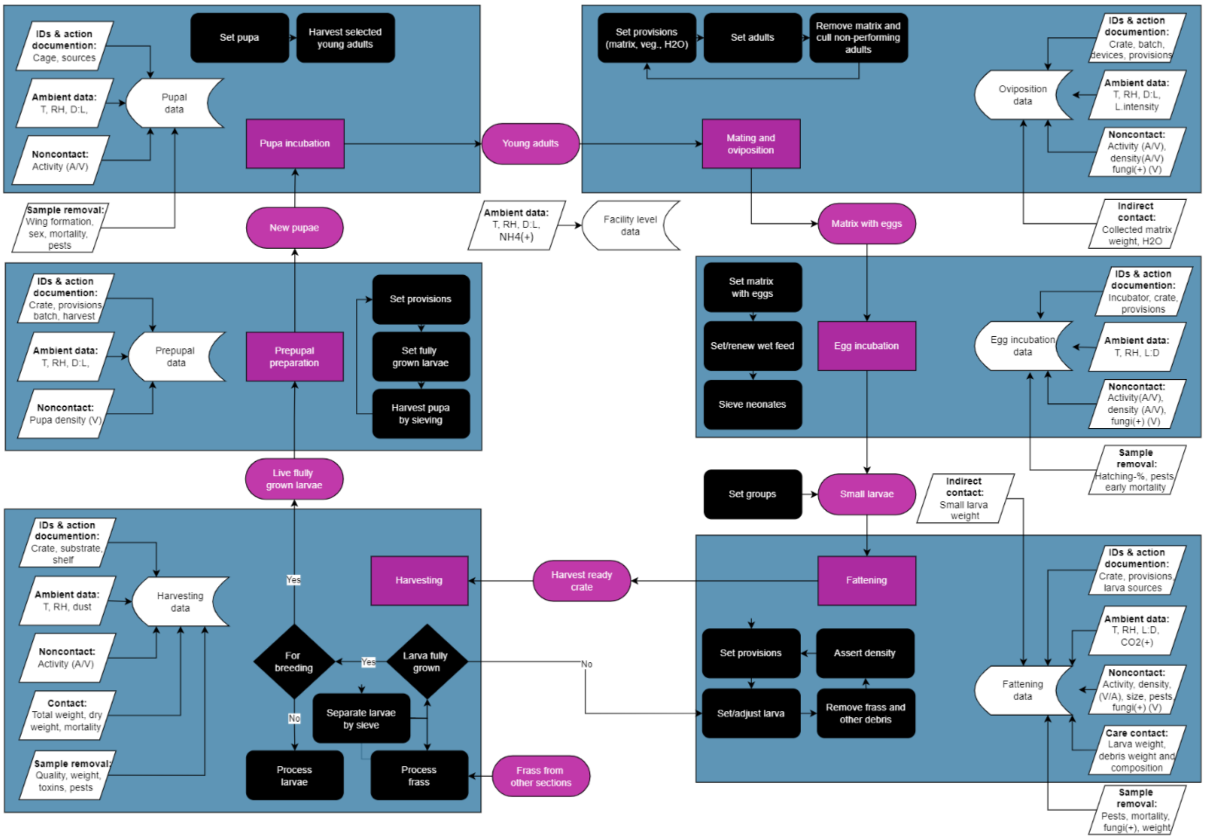
One of the main factors impacting the productivity of mealworm rearing system is the larval density. High densities may cause pupation inhibition, cannibalism, incomplete development and lower growth rates, likely due to competition (Weaver and McFarlane, 1990). High larval densities also affect the efficiency of digested food conversion and efficiency of ingested food conversion, overall comprising the yield of the rearing (Morales-Ramos and Rojas, 2015). Recently, Deruytter *et al.* (2022) studied larvae growth with five larval densities (0.5–8 larvae/cm^3) and four feed heights (1–8 cm). They found that at low larvae densities, the substrate height was less important, with a slight preference for a thicker layer. In contrast, at high(er) larval densities, a lower layer thickness resulted in better growth. In addition, overcrowding have a relevant impact on mating, as single couples are the most productive in terms of progeny produced per female (Morales-Ramos *et al.*, 2012). In their study, progeny per unit area increased to a maximum at a density of 14 adults/dm^2 and then declined sharply. Wu *et al.* (2009) estimated desirable rearing density of adult mealworm to be as high as 1.18 individuals per cm^2 (Wu *et al.*, 2009).

Mealworm mass rearing is a new industry, and thus, genetic breeding of the species is currently at the outset. The leading breeding companies and mealworm producers are interested in developing strains with valuable agronomic traits, namely rapid growth, high fertility, effective feed conversion and disease resistance. Such a genetically uniform and bred strains are however not available yet, but utilizing the new tools of genetic research may take mealworm genetic breeding forward quickly. Currently, the new insect producers need to start with a small breeding stock and reproduce the colony in repeated cycles. Typically, a small batch of fully grown larvae are selected at harvest and allowed to complete the metamorphosis and form a new breeding colony.

Cycle management requires farmer to make decisions on size of the breeding colony, and selection criteria. A successful decision making enables balanced cycle, but for sensible decisions the farmer needs information on reproduction capacity of the selected breeding colony and properties of available inputs, such as feed quality and how it affects larvae growth, feed conversion rate and survival.

All live stages take place in dry environments, but only partially visibly on surface. Typically substrate, pieces of vegetables or other individuals cover a major share of the densely living population.

Therefore, visual monitoring can access only part of the brood, but this can be sufficient for observing progress by automated visual observations. However, this might be a biased sample. Tenebrios are handled more intensively than Black Soldier Flies or Crickets, and the repeating sieving process creates a natural data collection point by direct contact. In monitoring, four data points per hour is sufficient. Tenebrios are sensitive to some fungi, and moisture and fungal growth should be monitored closely. The monitoring is mainly based on ambient environment or remote sensing (Figure 6). However, the production system details might vary, and influence the monitoring options. Developmental rates vary in tenebrio, and insect groups might be mixed at various stages. Detailed group ancestry documentation as well as biological performance evaluation might be challenging, if this mixing is not controlled and documented. Table 7 summarizes some key parameters of *T. molitor* throughput its life cycle.



T=temperature, RH=relative humidity, H2O=moisture, D:L=Dark:light cycle, L. = light, A=audio, V=visual, CO2=carbon dioxide.

Figure 6. Simplified flow chart sketching time-stamped sensing and tracking data that can be used for quality assurance and improvement in the biological mealworm production process. Technical flow chart is presented in D2.2 Figure 4.

Table 7. Minimum, average, and maximum values of different life cycle parameters of T. molitor, as reported in different works.

		Minimum	Average	Maximum
Number of eggs		77	250 280 414 400-500	500 576 1000
Length (mm)	Larvae	20 28	16 28	25 32
	Adults	12 15.5	-	16
Body mass (mg)	Larvae	75 130 140	111 120 126 191	160 182.7 190 220
	Adults	-	136	-
Duration (days)	Complete life cycle	75 90 181 280	80-83.7 189 294	90 120 196 630
	Egg stage	4 at 26-31 °C 4-6 5 at 35 °C 7 10	7 7.55 at 25 °C 9.2 12.6 at 20 °C 15	10 12 15 19 at 18-21 °C 34 at 15 °C
	Larva stage	57 87.7 110.8 at 30 °C	112 120 at 25 °C 151.15	202.5 216 240

Adapted from: Ribeiro, 2017.

4.1.7 Rearing environment's conditions

4.1.7.1 Temperature

To achieve a uniform batch of harvested larvae, mealworms are usually reared at a temperature of 25-28 ºC (Ghaly and Alkoaik, 2009; Kim *et al.*, 2015; Koo *et al.*, 2013; Selaledi *et al.*, 2020). In general, temperatures for insect development range from 10 °C (lower threshold) to 35°C (upper threshold) (Punzo and Mutchmor, 1980), while development in *T. molitor* occurs between 17 ºC (Koo *et al.*, 2013) and 30 ºC (Koo *et al.*, 2013; Ludwig, 1956). In this regard, the number of larval instars is higher and the period required to complete the instar development is shorter at 30 ºC (Ludwig, 1956). Even so, there are specific temperature requirements among the different stages of development of this species (Table 8).

The lethal and chill-coma temperatures are 40-44 ºC (Martin *et al.*, 1976) and 7-8 ºC, respectively, respectively, for exposure periods of 24 hours (Mutchmor and Richards, 1961; Punzo and Mutchmor, 1980). Table 8 summarizes temperature ranges of rearing *T. molitor* at different stages of life cycle.

4.1.7.2 Relative humidity (RH)

Mealworms show more flexibility to relative humidity than to temperature. The growth rate of *T. molitor* larvae is highly dependent on moisture, with best growth rates reported at 80-100% ambient RH (Table 9) (Alves *et al.*, 2016; Hardouin and Mahoux, 2003; Lardies *et al.*, 2014). In low humidity conditions, development is impaired as it is very slow at 30% RH and hardly proceeds at 13% RH (Fraenkel, 1950). On the other hand, high levels of moisture favor the growth colony contaminants (e.g., fungi, other microorganisms, mites), which can decrease the positive correlation between high temperature and quick development (Ribeiro *et al.*, 2018). Therefore, a relative humidity of 60% to 75% is desirable (Oonincx *et al.*, 2015; Punzo and Mutchmor, 1980; Spencer and Spencer, 2006). The water requirement for the larvae is minimal due to their ability to absorb water from the saturated air at 75 - 90% relative humidity, while adult mealworms are not able to absorb atmospheric water. Therefore, the addition of a water source (i.e., through vegetables) is crucial for adult stages and has even a beneficial effect on the larvae stage, since it promotes a faster growth (Hansen *et al.*, 2004; Ortiz *et al.*, 2016).

According to the literature, water has two important functions. Firstly, water has a positive effect on growth. Urs and Hopkins (1973) and Van Broekhoven *et al.* (2015) observed that mealworms have a better performance in indoor artificial rearing when the insects were supplemented with a source of water in addition to the dry diet. Moreover, Murray (1968) reported that when the mealworms larvae are deprived of water, they ingest lower amounts of food and are less efficient in converting the nutrients into body mass. Secondly, water can affect the content of nutrients of the larvae, although there are contrasting data in the literature. Oonincx *et al.* (2015) reported that the supplementation of the diets with a water source increases the water content but not the total fatty acids content of larvae. On the contrary, Urs and Hopkins (1973) observed that the availability of water increases the concentrations of total lipids. Nonetheless, both authors found no influence of water on mealworm fatty acid profile. Table 9 summarizes temperature ranges of rearing *T. molitor* at different stages of life cycle.

4.1.7.3 Light conditions

Light conditions (i.e., photoperiod) can strongly influence the development of mealworms. It is important to remember that the mealworm is a negative phototropic (or phototactic) species, thus it prefers dark environments (Balfour and Carmichael, 1928; Cloudsley-Thompson, 1953). For instance, adults and larger larvae tend to hide inside the substrate when light is on and come close to surface during dark periods. However, this response to photoperiod disappears under constant conditions (Cloudsley-Thompson, 1953).

Larval development is optimal under long-day conditions, while lower development times result under photoperiodic conditions of 14L:10D. The elusion rate is also dependent on photoperiod and promoted under long-day conditions, with 45.5% at 14L:10D versus 24.2% at 10L:14D (Kim *et al.*, 2015). In addition, pupation is induced by the photoperiod, as it occurs under a 12L:12D regime at 25ºC. Nevertheless, the interaction between light and temperature is a very important factor, in that the photoperiodic response was reversed at 30°C, as pupation was inhibited under 12L:12D and triggered under 18L:6D conditions (Tyshchenko and Ba, 1986). Recently Eberle *et al.* (2022) found that photoperiod influences the developmental time and growth rate. The highest survival rates and growth rates, and shortest developmental times, were observed in their study at 25 and 30 ◦C at constant darkness.

4.1.7.4 Ventilation

The oxygen amount is critical in mealworm rearing processes. Low oxygen concentration (hypoxia) increases the larval mortality, inducing hypertrophy of tracheae and overall affecting respiratory exchanges (Greenberg and Ar, 1996; Loudon, 1989, 1988). An oxygen concentration around 10.0-10.5% inhibits insect growth and leads to the development of abnormalities and alteration of the sex ratio (higher proportion of females in the population) (Loudon, 1988). On the other hand, the number of instars is reduced under hyperoxia (>40% O_2) conditions, resulting in lower larval biomass compared to normal oxygen values (Greenberg and Ar, 1996).

4.1.7.5 Interaction between factors

As mentioned before, the number and duration of instar stages, the mealworm development, and the capacity of different stages at absorbing water from air are directly affected by temperature and humidity.

The pupal stage is the stage more resilient to extreme conditions of temperature and relative humidity, whilst eggs and young larval stages are the most sensitive phases (Punzo and Mutchmor, 1980). Indeed, mealworm development is favored when both temperature and humidity lay in a certain range. Dick (1937), as example, reported that oviposition does not occur at temperatures below 14 ºC even at 65% relative humidity and is significantly reduced even when temperature is optimal (27 ºC) but humidity is low (20%). Hardouin and Mahoux (2003) similarly reported that the female reproductive activity is promoted at relative humidity values of 90-100%. At extremely dry conditions mealworm larvae cease completely the food ingestion and become inactive until relative humidity gets favorable again (Urs and Hopkins, 1973). Many studies demonstrated that extreme temperature and humidity conditions affect the mealworm development and survival. For instance, at temperatures below 10 ºC (Punzo, 1975; Punzo and Mutchmor, 1980) or 12.5 ºC (Kim *et al.*, 2015), water absorption is reduced, and the embryological development is not completed. Extremely dry conditions (12% relative humidity) elicit water losses from the eggs, which die due to desiccation (Punzo, 1975). However, the effect of either temperature or humidity on the mealworm life cycle is enhanced when one of these factors is at extreme levels. This means that the role of temperature on the development of mealworms is correlated with the relative humidity of the rearing and vice-versa (Punzo and Mutchmor, 1980). For example, at optimal temperatures of 25.0-27.5 ºC, mealworms can thrive even at extreme humidity conditions and long exposure periods. Moreover, a decreased humidity does not affect adults, larvae, or pupae at a temperature of 25 °C, but increases the mortality at 10°C (Punzo and Mutchmor, 1980).

4.1.7.6 Controlling rearing conditions

Even if mealworms can survive in a wide range of temperatures, small fluctuations from the optimal conditions can slow down the larva development. In large scale mass production facilities, moderate temperature stresses can cause uneven quality, resulting in losses when sorting the larvae or when separating the frass. The extended rearing time due to temperature stress increases the infrastructure cost per cycle as well. For these reasons, a careful temperature monitoring and management is essential in mealworm mass rearing (Ortiz *et al.*, 2016).

Energy cost and labor cost are important costs in mealworm production (Niyonsaba *et al.*, 2021). Controlling rearing conditions by heating or cooling or increasing ventilation needs energy. In addition to slowed growth, and impaired predictability, uncontrolled conditions may also increase mortality or increase the risk of pest and pathogens. This may lead to increased labor cost in terms of increased manual handling and rejection of bad patches.

In a large production facility with vertical growing system, temperature, humidity and concentration of gases can, however, vary markedly horizontally or vertically or between trays, depending on e.g. air flow or larvae activity, or temperature and humidity fluctuation outside the rearing facilities. For maintaining optimal rearing conditions regardless of tray location in the rearing facility, the parameters should be monitored in several spots or in the facility. A large data set observed utilizing affordable sensors and a predicting model could be used to keep optimal rearing conditions. Critical values for the measured variables should be determined in order to support decision making on whether to use energy or labor to adjust rearing conditions.

Table 8. Minimum, optimal, and maximum temperature values to rear T. molitor, as reported in different works.

	Minimum	Optimal	Maximum
Eggs	10 °C 15 °C 17 °C	23-27 °C 25 °C 25-27 °C	30 °C 35 °C
Larvae	10 °C 17 °C 20 °C	25 °C 27-28 °C	30 °C 35 °C
Pupae	10 °C 18 °C 21 °C	25 °C 27 °C 27.5 °C 28 °C 27-33 °C	35 °C
Adults	10 °C 14-16 °C	25 °C	35 °C

Adapted from: Ribeiro *et al.* (2018).

Table 9. Minimum, optimal, and maximum relative humidity values (%) to rear T. molitor, as reported in different works.

	Minimum	Optimal	Maximum
Eggs	12	60-75 70 75	98
Larvae	12 30	75 60-70 70	98
Pupae	12	70 75	98
Adults	12 20	70 75 90-100	98

Adapted from: Ribeiro *et al.* (2018).

4.1.8 Nutritional requirements

4.1.8.1 Macronutrients

In addition to a water source (i.e., fruits, vegetables, or agar), mealworm can be reared on wheat bran, which is an agricultural byproduct (Liu *et al.*, 2020; Ortiz *et al.*, 2016). The latter contains most of the necessary nutrients, although in sub-optimal proportions (Morales-Ramos *et al.*, 2011). Protein sources as beer yeast (Ghaly and Alkoaik, 2009; Oonincx *et al.*, 2015; Van Broekhoven *et al.*, 2015), casein (Murray, 1960; Rho and Lee, 2014) and soy protein (Hardouin and Mahoux, 2003; Morales-Ramos *et al.*, 2013) are accordingly added to complement the diet. Given that the diet is the milestone of a successful and convenient artificial rearing, studies have been carried out to test the influence of diet on several life parameters of the mealworm (Davis, 1970; Fraenkel, 1950; Morales-Ramos *et al.*, 2013, 2010; Rho and Lee, 2014; Van Broekhoven *et al.*, 2015), including fertility (Gerber and Sabourin, 1984; Morales-Ramos *et al.*, 2013; Urrejola *et al.*, 2011), number of instars (Morales-Ramos *et al.*, 2010), survival rate (Morales-Ramos *et al.*, 2010; Van Broekhoven *et al.*, 2015), the intensity and period of oviposition (Manojlovic, 1987; Morales-Ramos *et al.*, 2013) and progeny production (Gerber and Sabourin, 1984).

Mealworm lifecycle is highly conditioned by the dietary ratio protein (P): carbohydrate (C) (Martin and Hare, 1942; Rho and Lee, 2016, 2015, 2014; Urrejola *et al.*, 2011). Rho and Lee (2016) reported an optimal P:C ratio of 1:1 for lifespan and lifetime reproductive success, while Martin and Hare (1942) observed maximum growth at a minimum of 50% of carbohydrates and 15% -25% of proteins in diet. Fats becomes an inhibitory factor only at values exceeding 3% (Martin and Hare, 1942). The most beneficial supplement to diet is protein and the addition of yeast at several concentrations proved to maximize weight gain and food conversion rates and decrease mortality and development times (Oonincx *et al.*, 2015; Van Broekhoven *et al.*, 2015). The importance of nutrient balance depends also on the developmental stage. The intensity and period of oviposition is highly dependent on the quality of the ingested food (Morales-Ramos *et al.*, 2013). High quality diet result in high production of offspring by increasing the number of eggs and decreasing adult mortality (Gerber and Sabourin, 1984). Compared to food consisting of crude fibers and carbohydrates, a rich and high-quality diet result the body protein contents two-fold higher and body fat contents five to six-fold higher (Ramos-Elorduy *et al.*, 2002). Moreover, mealworms fed on low P:C feed have higher body lipid content (Rho and Lee, 2014).

For sustainable large-scale mass rearing, it is important to find a year around available and affordable substrate that meets the nutritional quality requirements of mealworm rearing. Side streams from food industry and former feedstuff products have accordingly shown high potential (Mancini *et al.*, 2019; Rumbos *et al.*, 2020). From the sustainability perspective, it would be important to utilize low-value feed materials which are not used elsewhere.

4.1.8.2 Protein

The dietary concentration of protein and the amino acid composition greatly influence *T. molitor* lifecycle, larval development time, survival, and weight gain (Morales-Ramos *et al.*, 2013; Oonincx *et al.*, 2015; Van Broekhoven *et al.*, 2015). Reported optimal ranges of protein concentration are 2-32% (Davis and Leclercq, 1969). Growth rate is significantly enhanced by presence of protein in that mealworms can pass from a fresh weight gain of 2.3-2.9 mg to a weight of 45.5-55.6 mg when switching from a free-protein diet to a diet supplemented with yeast (John *et al.*, 1979). In this regard, yeast is currently the best source of protein, even acting as a feeding stimulant. Other efficient protein sources that provide optimal effects are casein, and at a lower level, lactalbumin (Davis and Leclercq, 1969; Fraenkel, 1950). Within amino acids, alanine, arginine, aspartic acid, cystine, histidine, isoleucine, leucine, methionine, proline, and valine should be fed at equivalent levels to those found in larval tissues, whereas phenylalanine should be provided at concentrations half of the values found in the larval tissues. Two limiting amino acids, threonine, and tryptophan should be administered at twice the concentration found in larvae body (John *et al.*, 1979). It is important to remember that the presence of carnitine is absolutely necessary for the appropriate development of *T. molitor* (Hardouin and Mahoux, 2003).

T. molitor has a highly stable body protein content, as the protein composition of the mealworm does not change even when fed with diets varying 2–3-fold in crude protein (Van Broekhoven *et al.*, 2015). Adámková *et al.* (2020) found that both the nutritional value of *T. molitor*, especially the content of crude protein, amino acids, fat, and fatty acid profile can be affected by temperature and feed composition. They concluded that a higher proportion of protein diet could increase the content of crude protein in the insects. An increase in the temperature led only to a slight increase in the content of nitrogenous substances, in their study.

4.1.8.3 Fat

Similar to mealworm's protein content, fat composition is rather constant (i.e., rich in oleic, linoleic, and palmitic acids) even when fed on different diets, suggesting that the fatty acid composition is independent from the feeding diet (Oonincx *et al.*, 2015). Even so, the addition of low concentrations of lipids to dietary regimes is beneficial, whilst high quantities are unfavorable and potentially pernicious (Morales-Ramos *et al.*, 2013). Cholesterol is a necessary diet ingredient, while fat concentrations higher than 1% have no effect on any mealworm's lifecycle parameter (Fraenkel, 1950) and become an inhibitor factor at concentrations above 3% (Martin and Hare, 1942). Finally, lipids-rich diets promote the potential agglomeration of the substrate resulting in lower aeration and movement of mealworms, thus negatively interfering with air circulation and insect's respiration (Alves *et al.*, 2016).

4.1.8.4 Carbohydrates

Carbohydrates are crucial components of the mealworm diet as they strongly influence the growth of the insects. The optimal range of carbohydrates is 80-85%, while diets with only 20% carbohydrates results in very slow growth (Fraenkel, 1950). Although Fraenkel (1950) reported no significant differences between the growth of mealworms with glucose and starch, diets comprising starch, sucrose or lactose, and amino acid mixtures resulted in smaller mealworm growth. On the other hand, bacteriological dextrin as a carbohydrate source resulted in a weight gain two-fold higher compared to glucose (Davis, 1974).

4.1.8.5 Micronutrients

Vitamins are indeed necessary to promote the growth of mealworms, as larvae do not survive if fed with a vitamin-free diet of casein, fat, carbohydrate, salt mixture and cholesterol. However, this diet can be optimal for mealworms when supplemented with yeast or liver, which provide the necessary micronutrients (Martin and Hare, 1942). Martin and Hare (1942) also demonstrated that vitamins A, D, C, E, K, choline, thiamine, riboflavin, pyridoxin, nicotinic acid and pantothenic acid are important elements for the growth of mealworms.

4.1.8.6 Side stream products as feeding for Tenebrio molitor

As mentioned above, mealworms can survive on varied diets consisting of plant and animal-based substances. The larvae can utilize low value biomasses converting different side streams from agriculture and food industry into body mass. For economically sensible mass production, it is necessary to find low-price sidestreams with nutritional quality and composition that meets mealworm requirements. Valorisation potential of some of the side streams from food chain is limited either due to legal aspects, seasonality, transport and storability or unsuitability for insect production. A lot of research has recently been conducted with the aim of finding affordable and year-round available sidestreams that can be utilized in mealworm production. Especially, the underutilized side streams, that are currently not used in feed processing for other animals, have been in focus when trying to find solutions to make the food chain more sustainable.

A comprehensive review on use of vegetable-based byproducts in mealworm diet has been published recently by van Peer *et al.* (2021). Spent brewer's or distiller's grains, breadcrumbs or cookie remains, for example, have been successfully included in mealworm diets, with the exception that cinnamon in some bakery side streams has shown to be toxic for mealworm. Carrot is often used as moisture source in mealworm diet, but it can also be mixed with other vegetable sidestreams such as mixed peels of onion, potato, sweet potato, and cucumber. For optimal larvae performance it's, however, important to prepare the mix carefully so that the composition meets the nutritional requirements of mealworm larvae. Potato glycoalkaloids may be toxic to insects that are not adapted to feed on potato, but mealworm has shown to be more tolerant to potato glycoalkaloids than some sensitive beetles such as *Zophobas atratus*. (Rev. Peer *et al.*, 2021)

Suitability of some low-cost sidestreams from cereal and legume seed cleaning process such as triticale, barley, durum wheat, oat, vetch, pea, lupin, lentil, lucerne and broad bean have recently been tested for mealworm feeding (Rumbos *et al.*, 2021). Overall, the lupin and triticale byproducts efficiently supported complete larval development, from first instar to pupation, and gave the best results among the byproducts tested in terms of larval growth and survival, development time and feed utilization.

Agricultural residues such as leek foliage, cauliflower leaves, Belgian endive roots and Belgian endive white leaves can also be used as moisture source, as far as they are properly mixed. Lignocellulose-rich agricultural residues have been tested and wheat straw, rice straw, rice bran, rice husk and corn straw have shown to usable in mealworm diet, but they need pretreatments such as cutting into small pieces, washing or drying in a forced-air drying oven. (Rev. Peer *et al.*, 2021). Pretreatments with microbes has also shown potential for fiber-rich side streams before addition in mealworm diet (Zhang *et al.*, 2021)

4.1.9 Production technologies and separation

Mealworm production relies on trays where the development of larvae occurs and where adults can mate. The tray size is usually 65 × 50 × 15 cm (length × width × height, Figure 7), as these trays are easy to handle and prevent escaping of mealworms. The material of the tray may vary (i.e., wood, polyethylene, or fiberglass). It should be easy to clean and shall not promote the accumulation of bacteria and fungi. Multilevel racks or shelves are commonly used to hold the trays and save space (Ortiz *et al.*, 2016).

However, the current rearing processes relying on trays have multiple disadvantages. Firstly, they are not an open system and therefore waste products (frass) accumulate on their surface, favoring the proliferation of mites and other organisms that could reduce the development of mealworms (Ortiz *et al.*, 2016). To improve this system, the bottom of the trays can be replaced with a net, which allow the frass to fall down, preventing pernicious accumulation of wastes (Morales-Ramos *et al.*, 2012). Secondly, eggs laid inside trays are difficult to collect, and the tray must be removed and emptied from insects and food sources to enable egg removal. For this reason, adults are usually separated from the feeding substrate and placed in a specific tray before every oviposition period. Once eggs are laid, it is of fundamental importance to remove adults from the oviposited substrate to prevent egg cannibalism, which occurs when adults are deprived of food. In summary, the tray system demands a great amount of labor, as the number of processing steps and furniture is very high (Ortiz *et al.*, 2016).

An implemented system for rearing *T. molitor* has been described by Morales-Ramos *et al.* (2012). The system consists in stackable containers with nylon screens (0.5 mm openings) at the bottom, where larvae can thrive as they are provided with wheat bran and supplements as feeding source. By moving, larvae promote the falling of the frass that pass from the upper container to the lower one, reaching the last container of the stack, which collects the particles. Cleaning the container prevents mite infestations and allows the estimation of the quantity of feed consumed by the larvae, which provides useful information on the health of the rearing. Unfortunately, these containers cannot hold first to fourth instars, which must be temporarily (4–5 weeks at 25–28°C) reared in solid trays as they can pass through the net (Ortiz *et al.*, 2016). A further implementation of the screen trays consists in using a screen with opening dimensions of 0.85 mm, through which small larvae (first to sixth instars) can pass (Morales-Ramos and Rojas, 2015). The loss of food is limited, while the larvae fall on the bottom tray, where they can thrive by feeding on small food particles falling through upper trays. The great advantage of this screened container system is that adults do not need to be periodically removed from the container for oviposition, while their progeny can be collected from the bottom tray once they hatch (Ortiz *et al.*, 2016).

A crucial factor to consider in mealworm rearing is that the species displays the high level of variability in terms of developmental time, thus the life cycle is rarely synchronized (Morales-Ramos *et al.*, 2010; Morales-Ramos and Rojas, 2015). Given that instars are differently influenced by environmental factors and have different diet requirements, separation is an important part of the rearing process. Moreover, separation prevents cannibalization of pupae by larvae (Martin *et al.*, 1976; Morales-Ramos *et al.*, 2012; Morales-Ramos and Rojas, 2015; Weaver and McFarlane, 1990). Most separation procedures were previously performed manually by shaking the screened containers, whose size changes in function of the larval stage. However, a mechanized procedure was recently developed by Morales-Ramos *et al.* (2011). In this system, a circular separator comprising three-screen is governed by a conveyor, and there is no need of changing screen sizes. Large, medium, small larvae and frass particles can be easily and continuously separated. In particular, the openings of the first and second screens are rectangular to facilitate the passage of elongated-shaped larvae, while the last screen has regular square openings (0.5 mm) to enable the passage of frass particles (Ortiz *et al.*, 2016).

Separation also allows to select a breeding stock, by sampling a group of large larvae from the screen. This group continues its development in a tray. Unfortunately, cannibalism within the breeding stock can still occur as last instar larvae can have a development time range of over 30 days (Morales-Ramos and Rojas, 2015).

To ensure that all the larvae sizes grow equally and that they are well distributed in the crate, Deruytter *et al.* (2021) strongly recommended the placement of wet feed within 5 cm from the larvae. In small scale rearing, wet feed can be distributed manually, while upscaling to industrial volume requires wet feed dosing to be automatized.

4.1.10Harvesting and suppression

An electric vibrating mesh screen is commonly used to harvest the larvae, even if in small facilities this process is performed by hand, increasing the labor. Similarly, the pupae that will become adults has to be separated and this process needs mechanization to reduce cost and increase efficiency of most mealworm facilities (Ortiz *et al.*, 2016). The harvested larvae can be then dried or frozen; for example, Chinese mealworm farms exploit a microwave drying machine, which also allows long storage. Freezing is the most common practice to stabilize the mealworms but demands a great amount of energy (Lenaerts *et al.*, 2018).

The nutrient quality of mealworms processed by using techniques such as freeze drying and drying using vacuum oven or rack oven is rather similar. In fact, the composition and fatty acids profiles are similar between larvae processed with these methods, even if rack oven drying promoted Maillard reactions, which could improve the oxidative stability of the final product. At any rate, if we consider the energy cost in relation to the quality of dried mealworms, long process times should be avoided. Rack oven drying seems the best processing method, as it preserves the nutrient quality of the mealworms and it is the most convenient drying method. In this regard, rack oven drying has an energy cost of € 0.67/kg, which is significantly lower than the cost of vacuum oven drying (€ 3.24/kg) or freeze drying (€ 2.88/kg) (Kröncke *et al.*, 2019).

Figure 7. Conventional mealworm trays. (A) Larvae growing trays. (B) Adult reproductive trays. Photo: Jeffery Tomberlin (Ortiz et al., 2016).

4.2 Emissions and frass

During their development, mealworms can produce waste frass of approximately 2-3 times their final biomass, and a great proportion of the feedstock (i.e., wheat bran) is necessary to promote insect growth, whilst an impressive amount of egested frass needs to be treated. Currently, the management of waste frass increase the costs incurred by mealworm farms. The mealworm frass can be converted into valuable products, as it could be used as organic fertilizer. It has been also recently proposed to utilize mealworm frass as raw material for producing biochar, which is a charcoal used as a soil amendment and adsorbent, usually produced from wood chips, crop and agricultural wastes (Yang *et al.*, 2019).

4.3 Quality and risk profile

Notwithstanding the promising future of *T. molitor* as food and feed source, the nutritional value and safety risks linked with mealworm consumption depend on the feeding substrate (EFSA, 2015). Toxic metals can be acquired from feeding substrates and be accumulated in the insects body (Truzzi *et al.*, 2019; Vijver *et al.*, 2003). As consequence, insect-based products could be enriched of these toxic elements. As example, mealworms can accumulate cadmium, lead, and arsenic in their bodies if fed on organic substrates cultivated on polluted soils (Truzzi *et al.*, 2019; Vijver *et al.*, 2003).

The correlation between diverse feeding substrates and accumulation of heavy metals in mealworms was evaluated in a recent study. Wheat flour represented the least contaminated results of all considered metals, whilst the highest concentration of cadmium and lead was recorded from organic wheatmeal, and organic olive-pomace represented the largest source of mercury and arsenic. Even so, metal concentrations were below the legal limit of undesirable substances in animal feed (2002/32/EC) in all the tested substrates, which can be therefore considered safe in terms of heavy metal content. In particular, mercury was the only element that was accumulated in *T. molitor*'s body, whilst cadmium, nickel and arsenic penetrated in larvae and were excreted without accumulating. Interestingly, mealworms are a safe food from the point of view of mercury intake as their low selenium content provides a valuable protection against mercury toxicity. To conclude, risk of exposure to metals due to the consumption of mealworms is rather low and in compliance with European Union regulations (Truzzi *et al.*, 2019). Moreover, the gut of mealworm does not contain foodborne human pathogens such as *Salmonella* or *Listeria monocytogenes*, which suggests that this insect does not pose a risk for human health (Marshall *et al.*, 2016).

4.4 Costs and markets

Insect production is a new industry and thus there are no official statistics describing mealworm production volumes, producer prices or market size. Several market research, however, give estimates on current state of insect market and growth potential in the industry.

Fortune Business Insights (2022) for example estimates that the global insect protein market size is $189.32 million, in 2022 and is projected to grow to $856.08 million by 2029 (CAGR of 24,1% for the forecast period). The share of Coleoptera in the global insect protein market was estimated to be 24,19% in 2021.

Meticulous Research (2022) by contrast expects mealworm market to reach $1,27 billion by 2030, at a CAGR of 25,8% during the forecast period 2022–2030. In terms of volume, the mealworms market is expected to grow at a CAGR of 28,6% from 2022–2030 to reach 367,491.7 tons by 2030. In the report, the mealworms market is segmented into animal feed, aquafeed, pet food, food & beverages, and other applications.

In 2022, the animal feed segment is estimated to be the largest segment in the mealworms market. The growth of this segment is driven by the wide availability of mealworm products for use in animal feed, growing usage of mealworm-based products by feed manufacturers, and the high nutritional value of mealworms in animal nutrition. (Meticulous Research, 2022)

Of the five major geographies (North America, Europe, Asia-Pacific, Latin America, and the Middle East & Africa), Europe is expected to account for the largest share of the mealworms market in 2022. The large market share is attributed mainly to the presence of key mealworm manufacturers, increasing demand for alternative protein sources, high demand for protein-rich food and feed, and the presence of supportive regulation and policies for insect farming. (Meticulous Research, 2022)

Rabobank estimates that the demand for insect protein, mainly used as an animal feed and pet food ingredient, could reach half a million metric tons by 2030, up from 2020 market of approximately 10,000 metric tons (DeJong and Nikolik, 2021). In Rabobank's estimate, pet food is the largest market for insect proteins, followed by the aquafeed market. The small volume is one of the key reasons restricting the use of insect protein in aquafeed. The price of insect protein ranges between EUR 3 500 to EUR 5 500 per metric ton, which is significantly higher than fishmeal and soy protein, and may thus restrict the competitiveness of insect proteins as an alternative feed ingredient. Prices are however expected to drop by €2,000 per metric ton after the industry has completed the scale-up phase and the sector has reached maturity. (DeJong and Nikolik, 2022)

As a comparison, the size of animal feed protein ingredients global market exceeded USD 150 billion, in 2019, and is projected to register more than 6.0% CAGR between 2020 and 2026 (Ahuja & Singh, 2020).

Mealworm has an excellent nutritional profile expressed as content in proteins and in fats fibers, ashes, and dietary energy. Mealworm fatty acids profile and content can depend on multiple parameters, such as diet, environment, and life stage. Both the larvae body fat mass and the frass are rich in mono- and polyunsaturated fatty acids. These properties make mealworm interesting in human nutrition. However current EU novel food regulation doesn't allow processed insects in food market. Regarding chitin and chitosan, their growing application in the pharmaceutical, biomedical, cosmetic and food sectors, and water treatment is expected to drive market growth. (Rev. Errico *et al.*, 2021).

Table 10 summarises operational production costs and selling prices of mealworm, reported in selected studies. The production costs of insects are often quite high because of high labour costs, as routine procedures such as feeding are carried out manually. For example, Wouters *et al.* (2019) presented a model where labour costs were 62% of the total production costs. By using an automated feeding line for *T. molitor*, having the capacity of producing up to 50 tons of mealworms per year, labour costs could be reduced by 75%. Consequently, the minimal selling price required for a producer to cover the production costs decreased from 5.26 €/kg live weight to 3.71 €/kg. Upscaling the system to a production of 600 tons was estimated to reduce the production costs down to 2.48 €/kg. Besides saving costs by automation and upscaling, the feed price and feed efficiency played an important role as feed costs represented 29% of the total production costs. Reducing either the feed price by 50% or halving the feed consumption (i.e. enhancing feed efficiency) could have further reduced the break-even selling price of 600 tons unit down to 1.78 €/kg. (Wouters *et al.*, 2019).

Table 100. Prices of T. molitor larvae and operational costs of rearing as presented in scientific literature (table modified from Niyonsaba et al., 2021, Niemi et al., 2020).

Country	Price, €/t	Larvae type	Operational cost, €/t dried larvae[1]	Reference
Italy	10,850-17,000	Pet food, fresh	na	Mancuso *et al.* (2019)
EU/China	45,454/5,727	Dried	na	Ortiz *et al.* (2016)
Germany	32,330	Dried	na	Rumpold and Schlüter (2013)
The Netherlands	15,800-97,000	Fresh/dried	1,090-2,140	Meuwissen (2011)
China	900-165,800	Meal	na	Niemi *et al.* (2020)

[1] Operational costs may include: feed, water, electricity, labour, gas

4.5 Concluding remarks

Workflows in mealworm mass production include multiple tasks that are needed to regulate the growing conditions and optimize the impact of inputs on final products. Everyday decision making is needed in many of the steps in the workflow. Data on feed quality, growing conditions, and larvae growth are needed for informed decisions. For optimizing processes some systems for sensing important parameters in production facilities, modelling feed conversion and larvae growth and predict the course of process have been developed. Observed realtime data, and models could be included in a decision support system to help insect grower to make sensible decisions and optimize production processes.

Mealworms are also usually monitored at population-level (e.g. a crate), and sensing environmental conditions and the substrate are important for the performance of mealworms. However, as opposed to BSF, mealworms grow in rather dry substrates. One of the main factors impacting the productivity of mealworm rearing system is the larval density. High densities may cause pupation inhibition, cannibalism, incomplete development and lower growth rates, likely due to competition. The development of *T. molitor* occurs between 17 ºC and 30 ºC, but mealworms should usually be reared at a temperature of 25-27 ºC because fluctuations from the optimal conditions can slow down the larva development. Mealworms show more flexibility to relative humidity than to temperature. The desirable relative humidity is in most cases 70-75%, although even large deviations from these numbers may be tolerated. Controlling L:D cycle is important because photoperiod can strongly influence the development of mealworms, and the desirable pattern is 14L:10D. Another critical parameter is oxygen concentration, because low oxygen concentration increases the larval mortality. The oxygen concentration of at least around 10% and no more than 40% is required for mealworms to be viable.

Mealworms can utilize quite wide range of biomasses in their diets. In addition to a water source (i.e., fruits, vegetables or agar), mealworms can be reared on wheat bran which may be supplemented with a protein source. Mealworm lifecycle and performance is nevertheless conditioned by the dietary ratio protein: carbohydrate. However, studies have reported a wide optimal range (2-32%) of protein concentrations.

It is also important to take into account in mealworm rearing is that the species displays high level of variability in terms of developmental time. Therefore, the life cycle is rarely synchronized and this increases the challenges of monitoring the process with sensors and of responding to monitoring observations by using dynamic management measures.

4.6 References

Adámková, A., Mlček, J., Adámek, M., Borkovcová, M., Bednářová, M., Hlobilová, V., Knížková, i., Juríková, T. 2020. Tenebrio molitor (Coleoptera: Tenebrionidae)—Optimization of Rearing Conditions to Obtain Desired Nutritional Values. Journal of Insect Science 20. https://doi.org/10.1093/jisesa/ieaa100

Ahuja, K., Singh, S. 2020. Animal Feed Protein Ingredients Industry Analysis Report and Forecast, 2020 – 2026. Global Market Insight Report ID GMI2604. 530 p.

Alves, A.V., Sanjinez-Argandoña, E.J., Linzmeier, A.M., Cardoso, C.A.L., Macedo, M.L.R. 2016. Food value of mealworm grown on acrocomia aculeata pulp flour. PLoS One 11, 1–11. https://doi.org/10.1371/journal.pone.0151275

Balfour, C.E., Carmichael, L. 1928. The light reactions of the meal worm (Tenebrio molitor Linn). Am. J. Psychol. 40, 576–584.

Baur, A., Koch, D:, Gatternig, D., Delgado, A. 2022. Noninvasive monitoring system for Tenebrio molitor larvae based on image processing with a watershed algorithm and a neural net approach. Journal of Insects as Food and Feed

Cloudsley-Thompson, J.L., 1953. Studies in diurnal rythms. IV. Photoperiodism and geotaxis in *Tenebrio molitor* L.(Coleoptera: tenebionidae). in: Proceedings of the Royal Entomological Society of London. Series A, General Entomology. Wiley Online Library, pp. 117–132.

Davis, G.R.F. 1974. Protein nutrition of Tenebrio molitor L: XVII.—Improved Amino Acid Mixture and Interaction with Dietary Carbohydrate. Arch. Int. Physiol. Biochim. 82, 631–637.

Davis, G.R.F. 1970. Protein Nutrition of «Tenebro Molitor» L. XII. Effects of Dietary Casein Concentration and of Dietary Cellulose on Larvae of Race F. Arch. Int. Physiol. Biochim. 78, 37–41.

Davis, G.R.F., Leclercq, J. 1969. Protein Nutrition of «Tenebrio Molitor» L. Ix. Replacement Caseins for the Reference Diet and a Comparison of the Nutritional Values of Various Lactalbumins and Lactalbumin Hydrolysates. Arch. Int. Physiol. Biochim. 77, 687–693.

Deruytter, D., Coudron, C.L., Claeys, J. 2021. The influence of wet feed distribution on the density, growth rate and growth variability of Tenebrio molitor. J. Insects as Food Feed 7, 141–149.

Deruytter, D., Coudron, C.L., Claeys, J. 2022. The Effects of Density on the Growth and Temperature Production of Tenebrio molitor Larvae. Sustainability 14, 6234. https://doi.org/10.3390/su14106234

Dick, J. 1937. Oviposition in certain Coleoptera. Ann. Appl. Biol. 24, 762–796.

EFSA. 2015. Risk profile related to production and consumption of insects as food and feed. EFSA J. 13. https://doi.org/10.2903/j.efsa.2015.4257

Eberle, S., Schaden, L.-M., Tintner, J., Stauffer, C., Schebeck, M. 2022 Effect of Temperature and Photoperiod on Development, Survival, and Growth Rate of Mealworms, *Tenebrio molitor*. Insects. 13, 321. https://doi.org/ 10.3390/insects13040321

Errico, S., Spagnoletta, A., Verardi, A:, Moliterni, S., Dimatteo, S., Sangiorgio, P. 2021. Tenebrio molitor as a source of interesting natural compounds, their recovery processes, biological effects, and safety aspects. Comprehensive Reviews in Food Science and Food Safety. https://doi.org/10.1111/1541-4337.12863

Fortune Business Insights. 2022. Insect protein market size, share, and COVID-19 impact analysis, by product type (Coleoptera, Lepidoptera, Hymenoptera, Orthoptera, and others), application 8Food and beverages, animal feed, and pharmaceuticals and cosmetics), and regional forecast, 2022-2029. Market research report. 150 p.

Fraenkel, G. 1950. The nutrition of the mealworm, Tenebrio molitor L.(Tenebrionidae, Coleoptera). Physiol. Zool. 23, 92–108.

Gerber, G.H., Sabourin, D.U. 1984. Oviposition site selection in Tenebrio molitor (Coleoptera: tenebrionidae) 1. Can. Entomol. 116, 27–39.

Ghaly, A.E., Alkoaik, F.N. 2009. The yellow mealworm as a novel source of protein. Am. J. Agric. Biol. Sci. 4, 319–331.

Greenberg, S., Ar, A. 1996. Effects of chronic hypoxia, normoxia and hyperoxia on larval development in the beetle Tenebrio molitor. J. Insect Physiol. 42, 991–996.

Hansen, L.L., Ramløv, H., Westh, P. 2004. Metabolic activity and water vapour absorption in the mealworm Tenebrio molitor L.(Coleoptera, Tenebrionidae): real-time measurements by two-channel microcalorimetry. J. Exp. Biol. 207, 545–552.

Hardouin, J., Mahoux, G. 2003. Zootechnie d'insectes-Elevage et utilisation au bénéfice de l'homme et de certains animaux.

Hill, D.S. 2002. Pests of stored foodstuffs and their control. Springer Science & Business Media.

Jehan, C., Chogne, M., Rigaud, T., Moret, Y. 2020. Sex-specific patterns of senescence in artificial insect populations varying in sexratio to manipulate reproductive effort. BMC Evolutionary Biology 20:18. https://doi.org/10.1186/s12862-020-1586-x

John, A.-M., Davis, G.R.F., Sosulski, F.W., 1979. Protein Nutrition of Tenebrio molitor L. XX. Growth response of larvae (o graded levels of amino acids. Arch. Int. Physiol. Biochim. 87, 997–1004.

Jongema, Y., 2017. List of edible insect species of the world. Laboratory of Entomology, Wageningen University, Wageningen, The Netherlands.

de Jong, B., Nikolik, G. 2021. No Longer Crawling: Insect Protein to Come of Age in the 2020s. Scaling up in on the horizon. RaboResearch, Food&Agribusiness. Rabobank.

Kim, S.Y., Park, J. Bin, Lee, Y.B., Yoon, H.J., Lee, K.Y., Kim, N.J. 2015. Growth characteristics of mealworm Tenebrio molitor. J. Sericultural Entomol. Sci. 53, 1–5.

Koo, H.-Y., Kim, S.-G., Oh, H.-K., Kim, J.-E., Choi, D.-S., Kim, D.-I., Kim, I. 2013. Temperature-dependent development model of larvae of mealworm beetle, Tenebrio molitor L.(Coleoptera: Tenebrionidae). Korean J. Appl. Entomol. 52, 387–394.

Kröncke, N., Grebenteuch, S., Keil, C., Demtröder, S., Kroh, L., Thünemann, A.F., Benning, R., Haase, H. 2019. Effect of different drying methods on nutrient quality of the yellow mealworm (Tenebrio molitor L.). Insects 10, 1–13. https://doi.org/10.3390/insects10040084

Lardies, M.A., Arias, M.B., Poupin, M.J., Bacigalupe, L.D. 2014. Heritability of hsp70 expression in the beetle Tenebrio molitor: Ontogenetic and environmental effects. J. Insect Physiol. 67, 70–75.

Lenaerts, S., Van Der Borght, M., Callens, A., Van Campenhout, L. 2018. Suitability of microwave drying for mealworms (Tenebrio molitor) as alternative to freeze drying: Impact on nutritional quality and colour. Food Chem. https://doi.org/10.1016/j.foodchem.2018.02.006

Li, L., Zhao, Z., Liu, H. 2013. Feasibility of feeding yellow mealworm (Tenebrio molitor L.) in bioregenerative life support systems as a source of animal protein for humans. Acta Astronaut. 92, 103–109.

Liu, C., Masri, J., Perez, V., Maya, C., Zhao, J. 2020. Growth performance and nutrient composition of mealworms (Tenebrio molitor) fed on fresh plant materials-supplemented diets. Foods 9, 151.

Loudon, C. 1989. Tracheal hypertrophy in mealworms: design and plasticity in oxygen supply systems. J. Exp. Biol. 147, 217–235.

Loudon, C. 1988. Development of Tenebrio molitor in low oxygen levels. J. Insect Physiol. 34, 97–103.

Ludwig, D., 1956. Effects of temperature and parental age on the life cycle of the mealworm, Tenebrio molitor Linnaeus (Coleoptera, Tenebrionidae). Ann. Entomol. Soc. Am. 49, 12–15.

Majewski, P., Zapotoczny, P., Lampa, P., Burduk, R., Reiner, J. 2022. Multipurpose monitoring system for edible insect breeding based on machine learning. Sci Rep 12, 7892. https://doi.org/10.1038/s41598-022-11794-5

Mancini, S., Fratini, F., Turchi, B., Mattioli, S., Dal Bosco, A., Tuccinardi, T., Nozic, S., Paci, G., 2019. Former foodstuff products in Tenebrio molitor rearing: Effects on growth, chemical composition, microbiological load, and antioxidant status. Animals 9, 484.

Mancuso, T., Pippinato, L. and Gasco, L. 2019. The European insects sector and its role in the provision of green proteins in feed supply. Calitatea 20: 374-381.

Manojlovic, B., 1987. A contribution to the study of the influence of the feeding of imagos and of climatic factors on the dynamics of oviposition and on the embryonal development of yellow mealworm Tenebrio molitor L.(Coleoptera: Tenebrionidae). Zast. bilja.

Marshall, D.L., Dickson, J.S., Nguyen, N.H. 2016. Ensuring Food Safety in Insect Based Foods: Mitigating Microbiological and Other Foodborne Hazards, Insects as Sustainable Food Ingredients. Elsevier Inc. https://doi.org/10.1016/b978-0-12-802856-8.00008-9

Martin, H.E., Hare, L. 1942. The nutritive requirements of Tenebrio molitor larvae. Biol. Bull. 83, 428–437. https://doi.org/10.2307/1538240

Martin, R.D., Rivers, J.P.W., Cowgill, U.M. 1976. Culturing mealworms as food for animals in captivity.

Int. Zoo Yearb. 16, 63–70.

Meticulous Research. 2022. Mealworms Market by Product Type (Whole Mealworm, Mealworm Powder, Mealworm Meal), Application (Animal Feed, Aquafeed, Pet Food, Food & Beverages), End Use (Animal Nutrition, Human Consumption) - Global Forecast to 2030. Report ID: MRFB - 104578. 159 p.

Meuwissen, P. 2011. Insects as new protein source. A scenario exploration of market opportunities. Insecten als nieuwe eiwitbron. Een scenarioverkenning van de marktkansen. ZLTO, 's Hertogenbosch, the Netherland

Miryam, D., Bar, P.S.T., Oscherov, M.E. 2000. Ciclo de Vida de Tenebrio molitor (Coleoptera , Tenebrionidae) en Condiciones Experimentales. Comun. Cient. y Tecnol. UNNE 6 35–38.

Morales-Ramos, J.A., Kelstrup, H.C., Rojas, M.G., Emery, V. 2019. Body mass increase induced by eight years of artificial selection in the yellow mealworm (Coleoptera: Tenebrionidae) and life history trade-offs. J. Insect Sci. 19, 4.

Morales-Ramos, J.A., Rojas, M.G. 2015. Effect of larval density on food utilization efficiency of Tenebrio molitor (Coleoptera: Tenebrionidae). Journal of Economic Entomology 108, 2259–2267.

Morales-Ramos, J.A., Rojas, M.G., Kay, S., Shapiro-Ilan, D.I., Tedders, W.L. 2012. Impact of adult weight, density, and age on reproduction of Tenebrio molitor (Coleoptera: Tenebrionidae). J. Entomol. Sci. 47, 208–220.

Morales-Ramos, J.A., Rojas, M.G., Shapiro-Ilan, D.I., Tedders, W.L. 2011. Self-selection of two diet components by Tenebrio molitor (Coleoptera: Tenebrionidae) larvae and its impact on fitness. Environ. Entomol. 40, 1285–1294.

Morales-Ramos, J.A., Rojas, M.G., Shapiro-Ilan, D.I., Tedders, W.L. 2010. Developmental plasticity in Tenebrio molitor (Coleoptera: Tenebrionidae): Analysis of instar variation in number and development time under different diets. J. Entomol. Sci. 45, 75–90.

Morales-Ramos, J.A., Rojas, M.G., Shapiro-llan, D.I., Tedders, W.L. 2013. Use of nutrient self-selection as a diet refining tool in Tenebrio molitor (Coleoptera: Tenebrionidae). J. Entomol. Sci. 48, 206–221.

Murray, D.R.P. 1968. The importance of water in the normal growth of larvae of Tenebrio molitor. Entomol. Exp. Appl. 11, 149–168.

Murray, D.R.P. 1960. The stimulus to feeding in larvae of Tenebrio molitor L. J. Insect Physiol. 4, 80–91.

Mutchmor, J.A., Richards, A.G. 1961. Low temperature tolerance of insects in relation to the influence of temperature on muscle apyrase activity. J. Insect Physiol. 7, 141–158.

Niyonsaba, H., Höhler, J. Kooistra, J., Van der Fels-Klerx, H, Meuwissen, M. 2021. Profitability of insect farms. Journal of Insects as Food and Feed 7: 923-934.

Oonincx, D.G.A.B., Van Broekhoven, S., Van Huis, A., van Loon, J.J.A. 2015. Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLoS One 10, e0144601.

Ortiz, J.A.C., Ruiz, A.T., Morales-Ramos, J.A., Thomas, M., Rojas, M.G., Tomberlin, J.K., Yi, L., Han, R., Giroud, L., Jullien, R.L. 2016. Insect Mass Production Technologies, Insects as Sustainable Food Ingredients. https://doi.org/10.1016/b978-0-12-802856-8.00006-5

Van Peer, M., Frooninckx, L., Coudron, C., Berrens, S., Álvarez, C., Deruytter, D., Verheyen, G., Van Miert, S. 2021. Valorisation Potential of Using Organic Side Streams as Feed for Tenebrio molitor, Acheta domesticus and Locusta migratoria. Insects 12, 796.

Punzo, F. 1975. Effects of temperature, moisture and thermal acclimation on the biology of Tenebrio molitor (Coleoptera: Tenebrionidae).

Punzo, F., Mutchmor, J.A. 1980. Effects of temperature, relative humidity and period of exposure on the survival capacity of Tenebrio molitor (Coleoptera: Tenebrionidae). J. Kansas Entomol. Soc. 260–270.

Ramos-Elorduy, J., González, E.A., Hernández, A.R., Pino, J.M. 2002. Use of Tenebrio molitor (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. Journal of Economic Entomology 95, 214–220.

Rho, M.S., Lee, K.P. 2016. Balanced intake of protein and carbohydrate maximizes lifetime reproductive success in the mealworm beetle, Tenebrio molitor (Coleoptera: Tenebrionidae). J. Insect Physiol. 91, 93–99.

Rho, M.S., Lee, K.P. 2015. Nutrient-specific food selection buffers the effect of nutritional imbalance in the mealworm beetle, Tenebrio molitor (Coleoptera: Tenebrionidae). Eur. J. Entomol. 112, 251.

Rho, M.S., Lee, K.P. 2014. Geometric analysis of nutrient balancing in the mealworm beetle, Tenebrio molitor L.(Coleoptera: Tenebrionidae). J. Insect Physiol. 71, 37–45.

Ribeiro, N., Abelho, M., Costa, R., 2018. A review of the scientific literature for optimal conditions for mass rearing Tenebrio molitor (Coleoptera: Tenebrionidae). J. Entomol. Sci. 53, 434–454.

Ribeiro, N.T.G.M. 2017. Tenebrio molitor for food or feed: rearing conditions and the effects of pesticides on its performance 70.

Rumpold, B.A., Schlüter, O.K. 2013. Potential and challenges of insects as an innovative source for food and feed production. Innovative Food Science & Emerging Technologies 17, 1-11. https://doi.org/10.1016/j.ifset.2012.11.005

Rumbos, C.I., Karapanagiotidis, I.T., Mente, E., Psofakis, P., Athanassiou, C.G. 2020. Evaluation of various commodities for the development of the yellow mealworm, Tenebrio molitor. Sci. Rep. 10, 1–10.

Rumbos, C.I, Bliamplias, D., Gourgouta, M., Michail, V., Athanassiou, C.G. 2021. Rearing Tenebrio molitor and Alphitobius diaperinus Larvae on Seed Cleaning Process Byproducts. Insects. 12, 293. https://doi.org/10.3390/insects12040293

Selaledi, L., Mbajiorgu, C.A., Mabelebele, M. 2020. The use of yellow mealworm (T. molitor) as alternative source of protein in poultry diets: a review. Trop. Anim. Health Prod. 52, 7–16.

Spencer, W., Spencer, J. 2006. Management guideline manual for invertebrate live food species. EAZA Terr. Invertebr. TAG 1–54.

Stork, N.E. 2018. How many species of insects and other terrestrial arthropods are there on Earth? Annu. Rev. Entomol. 63, 31–45.

Truzzi, C., Illuminati, S., Girolametti, F., Antonucci, M., Scarponi, G., Ruschioni, S., Riolo, P., Annibaldi, A. 2019. Influence of feeding substrates on the presence of toxic metals (Cd, pb, ni, as, hg) in larvae of Tenebrio molitor: Risk assessment for human consumption. Int. J. Environ. Res. Public Health 16. https://doi.org/10.3390/ijerph16234815

Tyshchenko, V.P., Ba, A.S. 1986. Photoperiodic regulation of larval growth and pupation of Tenebrio molitor L.(Coleoptera, Tenebrionidae). Entomol. Rev.

Urrejola, S., Nespolo, R., Lardies, M.A. 2011. Diet-induced developmental plasticity in life histories and energy metabolism in a beetle. Rev. Chil. Hist. Nat. 84, 523–533.

Urs, K.C.D., Hopkins, T.L. 1973. Effect of moisture on growth rate and development of two strains of Tenebrio molitor L.(Coleoptera, Tenebrionidae). J. Stored Prod. Res. 8, 291–297.

Van Broekhoven, S., Oonincx, D.G.A.B., Van Huis, A., Van Loon, J.J.A. 2015. Growth performance and feed conversion efficiency of three edible mealworm species (Coleoptera: Tenebrionidae) on diets composed of organic by-products. J. Insect Physiol. 73, 1–10.

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P. 2013. Edible insects: future prospects for food and feed security. Food and Agriculture Organization of the United Nations.

Vijver, M., Jager, T., Posthuma, L., Peijnenburg, W. 2003. Metal uptake from soils and soil–sediment mixtures by larvae of Tenebrio molitor (L.)(Coleoptera). Ecotoxicol. Environ. Saf. 54, 277–289.

Wade, M., Hoelle, J. 2019. A review of edible insect industrialization: Scales of production and implications for sustainability. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/aba1c1

Weaver, D.K., McFarlane, J.E. 1990. The effect of larval density on growth and development of Tenebrio molitor. J. Insect Physiol. 36, 531–536.

Wouters, F., Schillewaert, S., Spranghers, T. 2020. Cost-effective insect rearing through automation and sidestream valorization. Abstract. Insecta 2020 conference.

Wu, S., Lin, H., Li, M., Tang, X. 2009. Determination of some important technique parameters in the course of breeding Tenebrio molitor. J. Econ. Anim. 13, 28–31.

Yang, S.S., Chen, Y. di, Kang, J.H., Xie, T.R., He, L., Xing, D.F., Ren, N.Q., Ho, S.H., Wu, W.M. 2019. Generation of high-efficient biochar for dye adsorption using frass of yellow mealworms (larvae of Tenebrio molitor Linnaeus)fed with wheat straw for insect biomass production. J. Clean. Prod. 227, 33–47. https://doi.org/10.1016/j.jclepro.2019.04.005

Zim, J., Sarehane, M., Mazih, A., Lhomme, P., Elaini, R., Bouharroud, R. 2022. Effect of population density and photoperiod on larval growth and reproduction of Tenebrio molitor (Coleoptera: Tenebrionidae). Int. J. Trop. Insect Sci. 42, 1795–1801. https://doi.org/10.1007/s42690-021-00707-0

CoRoSect

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101016953