

Table of

Preface	14
Reviewers	17
Photo credits	20
Introduction	
1. The potential of insects as food and feed	24
<i>A. van Huis and J.K. Tomberlin</i>	
Abstract	25
1.1 Introduction	26
1.2 Future of animal protein	26
1.3 Livestock, environment and health	27
1.4 How to tackle the meat crises?	30
1.5 Edible insects	33
1.6 Why edible insects?	36
1.7 From producing to consuming	41
References	44
2. Ecosystem services of insects	60
<i>M. Dicke</i>	
Abstract	61
2.1 Introduction	62
2.2 Products of insects	63
2.3 Ecosystem services	67
2.4 Conclusions	71
References	72

contents

3. Environmental impact of insect production	78
<i>D.G.A.B. Oonincx</i>	
Abstract	79
3.1 Introduction	80
3.2 Direct emissions of greenhouse gases and ammonia	80
3.3 Assessing environmental impact	81
3.4 Insects for human consumption	83
3.5 Insects for livestock consumption	85
3.6 Other insect products; honey and silk	86
3.7 Feed utilisation	87
3.8 Conclusions	89
References	90
Tropical production systems	
4. Introducing small production systems for edible insects	96
<i>A. van Huis</i>	
References	99
5. Small-scale production of crickets and impact on rural livelihoods	100
<i>R. Caparros Megido, É. Haubruge and F. Francis</i>	
Abstract	101
5.1 Introduction	102
5.2 Species and characteristics of cricket rearing	103
5.3 Conclusions	108
References	109

6. Palm weevil farming contributing to food security in sub-Saharan Africa	112
<i>F.J. Muafor, A.A. Gnetegha, E. Dounias, P. Le Gall and P. Levang</i>	
Abstract	113
6.1 Introduction	114
6.2 Marketing and socioeconomic potential of grubs in Cameroon	115
6.3 Reproductive material for palm weevil grubs farming	116
6.4 Palm weevil grubs farming technique on experimentation in Cameroon	116
6.5 Suitable substrate for rearing the African palm weevil	117
6.6 Required farming conditions and work schedule	119
6.7 Dissemination attempts and performance of small-scale grub farms in Cameroon	119
6.8 What future for insect based enterprises in sub-Saharan Africa?	122
6.9 Conclusions	123
Acknowledgements	124
References	124
7. Farming of grasshoppers for feed and food	126
<i>P. Haldar and C. Malakar</i>	
Abstract	127
7.1 Introduction	128
7.2 Species of acridids	128
7.3 Biology	129
7.4 Rearing conditions	129
7.5 Diet	130
7.6 Rearing equipment	130
7.7 Reproduction unit	130
7.8 Production unit	132
7.9 Hygiene and sanitation	135
7.10 Processing	135
7.11 Conclusions	136
References	136

Production technology and management

8. Insect production and facility design	142
<i>R. Kok</i>	
Abstract	143
8.1 Introduction	144
8.2 General considerations	144
8.3 Organism environmental requirements at various life stages	146
8.4 Heat and mass transfer considerations	149
8.5 Process types	156
8.6 Reactor types	161
8.7 Materials handling	162
8.8 Process control	164
8.9 Plant sub-units and support operations	164

8.10 Other issues	169
8.11 Conclusions	171
Acknowledgements	172
9. Breeding and maintaining high-quality insects	174
<i>K. Jensen, T.N. Kristensen, L.-H.L. Heckmann and J.G. Sørensen</i>	
Abstract	175
9.1 Insects as a new means to enhance food security	176
9.2 Current conditions and challenges for insect mass-rearing and production	176
9.3 Quality production animals	177
9.4 Genetic aspects of mass production	179
9.5 Optimal temperature and thermal adaptations	185
9.6 Optimal diet in production	187
9.7 Conclusions	192
Acknowledgements	192
References	192
10. Natural enemies in insect production systems	200
<i>J. Eilenberg, S.N. Gasque and V.I.D. Ros</i>	
Abstract	201
10.1 Characteristics of natural enemies in insect production systems	202
10.2 Diversity of natural enemies of the palm weevil <i>Rhynchophorus ferrugineus</i>	206
10.3 Insect viruses infecting crickets	211
10.4 Recommendations	216
10.5 Conclusions	218
References	218

Industrial production systems

11. Industrialization of insect farming	226
<i>J.K. Tomberlin</i>	
References	228
12. Black soldier fly: biology and mass production	230
<i>J.K. Tomberlin and J.A. Cammack</i>	
Abstract	231
12.1 Introduction	232
12.2 Soldier fly biology	232
12.3 Industrialization of black soldier fly production	234
12.4 Larval production for sale as a product	234
12.5 Adult management: heartbeat of an industry	236
12.6 Larval production for colony management	238
12.7 Hurdles to be addressed with using black soldier fly prepupae as animal feed	239
12.8 Conclusions	242
References	243

13. Industrialization of house fly production for livestock feed	248
<i>J.K. Tomberlin, C. Holcomb and S.K. van Leeuwen</i>	
Abstract	249
13.1 Introduction	250
13.2 Nutritional composition of house flies	250
13.3 Use as feed	252
13.4 House fly production	253
13.5 Future hurdles and conclusions	254
References	255
14. Mealworms, promising beetles for the insect industry	258
<i>N. Berezina</i>	
Abstract	259
14.1 Introduction	260
14.2 <i>Alphitobius diaperinus</i> – lesser mealworm	260
14.3 <i>Tenebrio molitor</i> – yellow mealworm	262
14.4 Outlook	266
References	267
15. Cricket rearing	270
<i>G. Mott</i>	
Abstract	271
15.1 Farming crickets	272
15.2 Species selection	272
15.3 Life cycle	274
15.4 Preparations for rearing crickets	275
15.5 Raising crickets	279
15.6 Mating crickets	282
15.7 Harvest	285
15.8 Processing	285
15.9 <i>Acheta domesticus</i> densovirus	286
15.10 Conclusions	286
References	287

Nutritional quality and processing

16. Nutrient content of insects	290
<i>M.D. Finke and D.G.A.B. Oonincx</i>	
Abstract	291
16.1 Introduction	292
16.2 Nutrient content of insects	292
16.3 Life stage effects on nutrient composition	303
16.4 Dietary effects on insect nutrient composition	304
16.5 Environmental effects on insect composition	306
16.6 Processing effects on insect nutrient composition	306
16.7 Conclusions	308
References	308

17. Insect processing	318
<i>B.A. Rumpold, S. Bußler, H. Jäger and O. Schlüter</i>	
Abstract	319
17.1 Introduction	320
17.2 Decontamination	320
17.3 Drying	322
17.4 Comminution	324
17.5 Protein extraction	325
17.6 Lipid extraction	327
17.7 Chitin extraction	330
17.8 <i>Tenebrio molitor</i> and browning	332
17.9 Potential insect processing pathways	335
17.10 Conclusions	338
Acknowledgements	338
References	338

Regulation, ethics and promotion

18. Health risks and EU regulatory framework	346
<i>N. Meijer and H.J. van der Fels-Klerx</i>	
Abstract	347
18.1 Introduction	348
18.2 Health risks	348
18.3 EU regulatory framework	351
18.4 Food and feed safety management systems	355
18.5 Conclusions	358
References	359
19. Ethical issues in insect production	364
<i>H. Röcklinsberg, C. Gamborg and M. Gjerris</i>	
Abstract	365
19.1 Introduction	366
19.2 Social and ethical feasibility	367
19.3 Animal welfare research	370
19.4 Animal death and integrity	372
19.5 Conclusions	375
Acknowledgements	376
References	376
20. Creating an enabling environment	380
<i>P. Vantomme</i>	
Abstract	381
20.1 Introduction	382
20.2 Changing context and appreciation of food	382
20.3 Global awareness on insects as food since 2008	383
20.4 Enabling conditions for international agencies	385

20.5 Enabling conditions at country level	387
20.6 Role of public and private media and of civil society groups, including donor and investment communities	390
20.7 Conclusions	393
References	394
21. Product development and promotion	398
<i>M. Shockley, R.N. Allen and D. Gracer</i>	
Abstract	399
21.1 Introduction	400
21.2 Product development	401
21.3 Promotion	407
21.4 Conclusions	416
References	416
Appendix 1. Entopreneurs.	420
Future prospects	
22. Future prospects of insects as food and feed	430
<i>A. van Huis and J.K. Tomberlin</i>	
Abstract	431
22.1 Introduction	432
22.2 Which insect species	432
22.3 Genetics	434
22.4 Nutrition	434
22.5 Rearing conditions and facility design	435
22.6 Diseases and pests	436
22.7 Insect welfare	436
22.8 Processing	437
22.9 Food safety and legislation	437
22.10 How to convince consumers	438
22.11 Future of the edible insect sector	439
References	440
About the editors	446
Dr Arnold van Huis	446
Dr Jeffery K. Tomberlin	447

Preface

In tropical countries, insects have been a food source for a very long time, and the local population has an intricate knowledge about which species can be eaten, when and how they can be harvested, and which methods to use for conserving, preparing and consuming the insects. In the western world, this knowledge is absent as insects were never considered as food. However, insects are farmed by private companies as feed for pets, birds, fish, reptiles, etc. This utilisation is only a small niche market and the volumes produced are rather limited.

There is an increasing awareness that with the growing world population and increasing welfare that business as usual for the production of animal proteins is not an option. The land area available on our planet to satisfy the increasing demand for animal proteins is not enough. Besides, there are concerns about the environmental footprint of producing livestock (greenhouse gas and ammonia emissions), about infectious diseases of vertebrate animals that can naturally be transmitted to humans (zoonosis). For those reasons, society is receptive to the idea of searching alternative protein sources. Although it was known in the western world that insects are eaten in the tropics, only now they are considered as an option to be used both as human food and animal feed. Only since the last ten years there is an increasing interest to farm insects as a new source of protein for humans and for animals. This in particular when considering the lower environmental impact when compared to the conventional protein products.

However, to go from a niche market to producing edible insects at an industrial level is new. The only examples of mass rearing insects are those used in pest control. One example is the sterile insect technique in which large numbers of sterile insects are released into the wild. The sterile males compete with wild males to mate with the females. Females that mate with a sterile male produce no offspring, thus reducing the next generation's population. Insects that have been controlled (eradicated) this way are screw-worm flies, fruit flies and tsetse flies. Biological control companies have experience in rearing insects to control agricultural



pests (i.e. natural enemies, such as predators and parasitoids). However, the companies that produce insects as feed for animals are rather small with a lot of labour involved making it too expensive to be competitive to conventional feed products.

So, the field of rearing insects for either human food or animal feed is new. Companies are engaged in automating the system in order to bring the price down. However, there are many challenges. To make it interesting to rear insects, such approaches have to be done sustainably and environmental impact should compare with the farming of common production animals. What kind of production design and what kind of facilities are needed to farm the insects in an optimal way? Can we fine tune the rearing technique to respond to the biological requirements of the target species? What about using different strains of insects and how can we maintain a high quality of the insects (genetics). What kind of diets are we going to use taking into account the price and the large influence substrates have on the development of the insect and on the nutritional value of the end product. Of particular interest is the use of organic side-streams as this would largely contribute to a circular economy. Other factors of importance to the nutritional quality are for example the abiotic conditions and the stage of the insects to be harvested. Also, we have a lot of knowledge about entomopathogens to kill pest insects, but very limited knowledge about diseases and pests that occur in insect rearing. What about insect welfare? Does the killing of thousands of insects for food or feed morally equal the slaughtering of one cow? Then after harvesting the larvae, what is done with the substrate and how to process the insects? How to deal with chitin, protein and oil? Finally, the product needs to be marketed. When insects are used as food then consumer attitudes play an important role and what kind of strategies to use to convince the consumer? Another very important issue in such an innovative sector is the legislative framework which is often not conducive. What kind of enabling conditions are required for the edible insect industry to thrive?

Finding answers to all these questions served as the impetus for bringing together a diverse group of researchers and practitioners from around the world to develop this book dealing with all aspects of farming insects and developing methods for efficiently bringing insect-related products to the consumer.

In order to improve the quality of the book most chapters have been subjected to a peer review process. We tried to find the best independent subject experts around the globe to do so. Most chapters have been checked for accuracy and readability by at least one reviewer, most often two and sometimes even three reviewers. The detailed feedback, from a range of expert reviewers, ensures that that we deliver relevant, cutting edge, and high quality information useful for students, teachers, practitioners, and researchers. We wish to thank all reviewers, listed on the next page for the willingness to check the chapters and provide their valuable comments.

The editors and Wageningen Academic Publishers want to thank the Uyttenboogaart-Eliassen Foundation (UES; <http://tinyurl.com/y77pkj6b>) in the Netherlands for their generous grant to develop the e-learning module attached to this book (<https://e-insects.wageningenacademic.com>). The grant also allowed the incorporation of specially made high quality photographs both for the book and the e-learning module. The module enables readers to test whether they have learned from the book and to get feedback.

Arnold van Huis and Jeffery K. Tomberlin

credits

The photographs at the beginning of each section and of each chapter have been made and are copyrighted by Hans Smid (bugsinthepicture.com), except for the photograph in Chapter 2, which was made by Nina Fatouros (bugsinthepicture.com). The photographs of Hans Smid were optimized for increased depth of field by making multiple images taken at various distances with a camera (Canon M5, Tokyo, Japan) mounted on a Stackshot automated macro rail (Cognisys, Traverse city, MI, USA). Resulting stacks of images were processed in Zerene stacker software vs 1.04 (Zerene systems, Richland, WA, USA). The following insect species are shown:

Sections

- ▶ Introduction
 - ▶ Tropical production systems
 - ▶ Production technology and management
 - ▶ Industrial production systems
 - ▶ Nutritional quality and processing
 - ▶ Regulation, ethics and promotion
 - ▶ Future prospects
- Lucilia sericata*
Freeze-dried locusts
Freeze-dried *Alphitobus diaperinus*
Hermetia illucens
Freeze-dried crickets
Lucilia sericata
Calliphora vomitoria

Chapters

- ▶ 1 *Lucilia sericata*
- ▶ 2 *Trichogramma brassicae* parasitizing an egg of *Pieris brassicae*
- ▶ 3 *Pachnoda marginata*
- ▶ 4 *Imbrasia belina* (sun-dried)
- ▶ 5 *Gryllus bimaculatus*
- ▶ 6 *Rhynchophorus ferrugineus*
- ▶ 7 *Locusta migratoria*
- ▶ 8 *Alphitobus diaperinus*
- ▶ 9 *Gryllobates sigillatus*
- ▶ 10 *Zophobas morio*
- ▶ 11 *Calliphora vomitoria*
- ▶ 12 *Hermetia illucens*
- ▶ 13 *Musca domestica*
- ▶ 14 *Tenebrio molitor*
- ▶ 15 *Acheta domesticus*
- ▶ 16 *Blaptica dubia*
- ▶ 17 *Galleria mellonella*
- ▶ 18 *Omphisa fuscidentalis* (dried larvae)
- ▶ 19 *Gryllus assimilis*
- ▶ 20 *Apis mellifera*
- ▶ 21 Freeze-dried insects for human consumption
- ▶ 22 *Bombyx mori* (canned pupa)

1.



● *Lucilia sericata*

The potential of insects as food and feed

A. van Huis^{1*} and J.K. Tomberlin²

¹Laboratory of Entomology, Wageningen University, P.O. Box 16, 6700 AA Wageningen, the Netherlands; ²Department of Entomology, Texas A&M University, TAMU 2475, College Station, TX 77843-2475, USA; arnold.vanhuis@wur.nl

Abstract

Insect production has gained recognition globally as a viable economy in terms of protein production for food and feed. While many tropical countries have practiced entomophagy for millennia, western nations are just now tapping into this tremendous resource. The purpose of this text is to review the many facets related to insect production ranging from examining the diversity of arthropods currently being mass-produced, ethics of such systems, to industrialized processes currently employed to meet the growing demand. While the architecture from production of the insect to packaging is still in its infancy, this growing sector of agriculture is presented with a unique opportunity to address potential hurdles prior to their encounter through communication, education, and practice.

Keywords: edible insects, insects as food and feed, animal protein, alternative protein sources, environment, organic side streams

1.6.4 Ability to convert organic side streams

FAO (2011) estimated that ‘roughly one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tonnes per year’. The value of the lost and wasted food has been estimated to be 750 billion US\$ (The Economist, 2014). Most of it is vegetables (23%), followed by meat (21%), fruits (19%) and cereals (18%) (Figure 1.3). Besides, this loss and waste is associated with approximately 173 billion cubic meters of water consumption per year and 198 million hectares of cropland per year (Lipinski *et al.*, 2013).

The use of side streams to grow insects is of course a very interesting option. Most considered as insects as feed are the black soldier fly and the house fly. The capacity to live on organic side streams seems to be somewhat larger for the black soldier fly. Both have quite different life cycles in which the advantage of the house fly is their tremendous reproductive capacity (Figure 1.4). However also other fly species such as the blow fly, *Lucilia sericata*, and face fly, *Musca autumnalis*, can be considered (Čičková *et al.*, 2015). For insects for human consumption the yellow mealworm and crickets can also be grown on organic side-streams, in particular fruit and vegetable remains as well as dried distillers grains with solubles can be considered. An overview of these species grown on different types of organic side streams is given in Table 1.5. Also, a list is given of references indicating which insect species can be fed to pigs, poultry, to animals in general and to a number of fish species (Table 1.6). As alternatives for fish meal plant proteins (soya protein, corn gluten, pea meal and wheat gluten) have been and will probably continue to be the main choice when replacing fishmeal in aquaculture. However, these products have limitations due several nutritional drawbacks compared to fishmeal (Lock *et al.*, 2015; Olsen and Hasan, 2012) particularly in diets for carnivorous species, which are not adapted to plant feed. Besides, there is a relative low content of proteins, the amino acid profile is unbalanced, and the fibre content is high. Anti-nutritional components are present, reducing digestion or absorption of nutrients, counteract the function of vitamins and may even induce toxicity. Plant proteins also compete with use for human consumption.

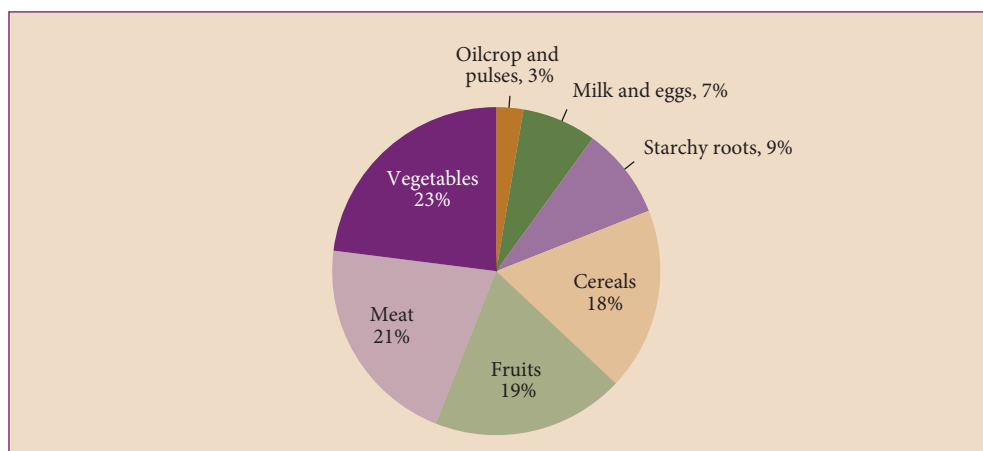


Figure 1.3. Global economic costs of food wastage (750 billion US\$), by commodity, 2007 (The Economist, 2014).

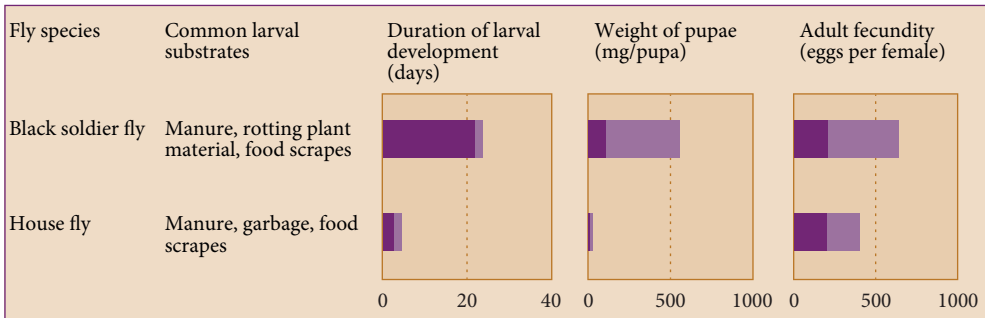


Figure 1.4. Comparison of life histories (under optimum conditions) of some fly species used for biodegradation (Čičková *et al.*, 2015).

Table 1.5. Insects species able to convert certain types of organic waste streams and references.

Insect species	Organic side streams and references
Black soldier fly	<ul style="list-style-type: none"> organic waste (Čičková <i>et al.</i>, 2015; Diener <i>et al.</i>, 2011b; Leong <i>et al.</i>, 2015; Ooninx <i>et al.</i>, 2015a; Pastor <i>et al.</i>, 2015; Surendra <i>et al.</i>, 2016) manure (Lalander <i>et al.</i>, 2015; Li <i>et al.</i>, 2011; Newton <i>et al.</i>, 2005a; Ooninx <i>et al.</i>, 2015b; Zhou <i>et al.</i>, 2013); pig manure (Newton <i>et al.</i>, 2005b; Wang <i>et al.</i>, 2013); cattle manure (Liu <i>et al.</i>, 2008; Myers <i>et al.</i>, 2008; Rehman <i>et al.</i>, 2017); chicken manure (Erickson <i>et al.</i>, 2004; Sheppard, 1983; Sheppard <i>et al.</i>, 1994); kitchen waste (Driemeyer, 2016) coffee pulp (Lardé, 1989, 1990) vegetables (Pineda Mejia, 2015; Rehman <i>et al.</i>, 2017; Spranghers <i>et al.</i>, 2016; Supriyatna <i>et al.</i>, 2016) catering waste (Jeon <i>et al.</i>, 2011; Spranghers <i>et al.</i>, 2016; Zheng <i>et al.</i>, 2012a,b) municipal organic waste (Diener <i>et al.</i>, 2009, 2011a; Gabler, 2014) straw (Manurung <i>et al.</i>, 2016; Nicks <i>et al.</i>, 2003; Zheng <i>et al.</i>, 2012a) dried distillers grains with solubles (Spranghers <i>et al.</i>, 2016; Webster <i>et al.</i>, 2015) sorghum and cowpea (Tinder <i>et al.</i>, 2017)
House fly	<ul style="list-style-type: none"> organic waste (Čičková <i>et al.</i>, 2015; Pastor <i>et al.</i>, 2015; Ramos-Elorduy and Morales, 1989) manure (Shah <i>et al.</i>, 2016); pig manure (Čičková <i>et al.</i>, 2012a,b; Roffeis <i>et al.</i>, 2015; Wang <i>et al.</i>, 2013; Zhang <i>et al.</i>, 2012); poultry (El Boushy, 1991; Teotia and Miller, 1974); cattle (Hussein <i>et al.</i>, 2017) municipal organic waste (Ocio <i>et al.</i>, 1979)
Yellow mealworm	<ul style="list-style-type: none"> organic waste (Ooninx <i>et al.</i>, 2015a) vegetables (Ramos-Elorduy <i>et al.</i>, 2002; Van Broekhoven <i>et al.</i>, 2015) dried distillers grains with solubles (Van Broekhoven <i>et al.</i>, 2015)
Crickets	<ul style="list-style-type: none"> organic waste (Ooninx <i>et al.</i>, 2015a) vegetables/cereals (Caparros Megido <i>et al.</i>, 2015; Miech <i>et al.</i>, 2016) weeds (Miech <i>et al.</i>, 2016)
<i>Cydia pomonella</i>	<ul style="list-style-type: none"> wastewater sludges (Brar <i>et al.</i>, 2008)