Research on the usefulness of computer model in assessing the G-force impact on honeybees (*Apis mellifera*) – current stage of the *BeeGs* project

Dagmara Stasiowska

AGH University of Science and Technology, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering, Krakow

Abstract: Every space travel is associated with the appearance of a number of stressors. One of the most violent moments is the launch when many G-force increases appear. As the vision of Martian settlement becomes more real nowadays, there is a need to establish a method of food production. One of the critical elements of such a method is pollinators' presence on site, such as honeybees (*Apis mellifera*). The *BeeGs* project was started in 2019 and aims to examine the impact of the G-force on honeybee queen fertility. As its final result, the author aims to check if the computer model of a colony with a G-forced queen is useful. In the paper, the current stage of the project is described and future work on the computer model is mentioned.

Keywords: computer modelling, G-force, honeybee, fertility

STAN OBECNY PROJEKTU *BeeGs* –
BADANIA NAD PRZYDATNOŚCIĄ MODELU KOMPUTEROWEGO
DO OCENY WPŁYWU PRZECIĄŻEŃ NA PSZCZOŁY MIODNE

Streszczenie: Każda podróż kosmiczna wiąże się z występowaniem licznych stresorów. Jednym z najbardziej niebezpiecznych momentów lotu jest start rakiety, generujący liczne przyrosty wartości przeciążeń. Z uwagi na coraz bardziej realną wizję osiedlania się na Marsie należy określić, w jaki sposób produkowane będzie tam pożywienie. Jednym z krytycznych elementów systemu produkcji żywności jest obecność zapylaczy takich jak pszczoła miodna (*Apis mellifera*). Projekt *BeeGs* rozpoczął się w 2019 roku, a jego celem jest ustalenie wpływu przeciążeń na matki pszczele. Ostatecznym rezultatem ma być ocena, czy model komputerowy rodziny pszczelej, w którym uwzględniony został fakt poddania matki przeciążeniom, przewiduje w sposób wiarygodny dalszy rozwój takiej rodziny. Artykuł opisuje obecny stan rozwoju projektu oraz wskazuje na przyszłe prace dotyczące modelu komputerowego.

Słowa kluczowe: modelowanie komputerowe, przeciążenia, pszczoła miodna, płodność

https://doi.org/10.7494/978-83-66727-83-0_10

1. Introduction

On the 20th of July 1969 for the first time in history human being stepped on another celestial body – the Moon. Since then, this act was repeated by another 11 people and the human desire to discover and settle in other worlds was constantly growing. National Aeronautics and Space Administration (NASA) along with European Space Agency (ESA) and several other national agencies and commercial companies in 2017 started a programme aiming to return to the Silver Globe (NASA 2020). Elon Musk, the founder of SpaceX, the biggest private company in the space sector, announced that the first human crew will land on Mars in 2029 (Elon Musk on Twitter 2022).

Despite the stage of the above-mentioned projects, one thing is sure – yet in this or the next decade people will become an interplanetary species. Along with that, many subsystems have to be developed to make it happen. Although there are many uncertainties, two aspects will most probably not change. Firstly, people will travel to other celestial bodies with rockets which generate plenty of G-force increases during the launch and which cannot be avoided in any way. Secondly, the crew will need to eat. Therefore, among many others, an on-site food production method will need to be established.

A significant role in food production is played by pollinators. Food and Agriculture Organization of the United Nations (FAO) claims that close to 75% of the world's crops, producing fruits and seeds for human consumption, depend, at least to some extent, on pollinators (FAO 2018). Although not all known plants require insect pollination, for the sake of astronauts' physical and psychological well-being their diet should possibly be as rich as possible. As traditional on-site meat production would be very resource-demanding, other sources of important micro- and macro-elements, such as zinc, magnesium or potassium, should be provided. Such sources are for example sunflower (Anjum et al. 2012, Petraru et al. 2021) or pumpkin (Glew et al. 2006) seeds – those however strongly depend on proper, insect-induced, pollination. Moreover, for some types of fruits included in many proposed future moon/Martian settlers' diets (e.g. strawberries) insect pollination is a key factor for their taste and quality (Wietzke et al. 2018), also when it comes to their storage potential.

Until now, several studies on honeybees' performance in space were done. In the 1980s research on their survival, behaviour and comb construction in microgravity was done (Vandenberg et al. 1985). Bee Enclosure Module (B.E.M) was taken on board of Space Shuttle *Discovery*, during mission STS-13. Maximum acceleration during the space shuttle's launch was around 3 Gs (*Space Shuttle Launch Motion Analysis* 2011). The control sample, stored at Johnson Space Centre, was centrifuged to simulate launch and ascent conditions. Queen on board the Space Shuttle laid approximately 35 eggs. However, all of them failed to hatch after transferring to a standard hive after returning to the Earth. Surprisingly, as the survival of honeybees was also studied, it appeared that after the experiment 120 specimens died in the tested sample and 350 in the control one (Vandenberg et al. 1985).

Two other experiments with different species of bees have been recorded in history. In 1982 onboard Space Shuttle *Columbia* during the STS-3 mission Insects in Flight Motion Study was done. Flies, bees and moths were studied. The main observation was different flight patterns in microgravity (*Onboard STS-3* 1982). The last experiment was supposed to be done during the *Challenger* STS-107 mission in 2003 (*Space Shuttle – Mission Archives –TS-107* 2003), this time on carpenter bees. However, this study has not been realized as the space shuttle exploded during the start in one of the biggest disasters in the history of space exploration.

The *BeeGs* project aims to fill the gap in the knowledge on the impact of the G-force itself on honeybees (*A. mellifera*) survivability, condition and fertility. Such knowledge could enable us to design better transporters for bees and to answer if this species could be used in future Martian greenhouses.

2. Methodology

The realisation of the *BeeGs* project required designing a dedicated tool for specimens' examination. *BeeO!Logical* is a payload designed for usage in a sounding rocket. It ensures stable conditions, same for both samples, test and control one. As the device has two, identical copies it is ensured that internal conditions are comparable and the only external factor changing is a G-stress.

BeeO!Logical, when completely assembled, is a standard size for such devices – 3U (10 cm × 10 cm × 30 cm). It consists of 4 main parts: an anti-shock case, thermal isolation, electronic box and biological boxes. *BeeO!Logical*'s second iteration can be seen in Figure 1. Thanks to the onboard computer and set of sensors it enables to gather data on specimens' respiration levels during the rocket flight. Its mechanical properties ensure safe and stable experiment conditions.

The anti-shock case is the most external part of the payload. It is made of stainless steel, 1.5 mm thick. Its main purpose is to protect all inner elements from external forces and tensions. It is also supporting thermal isolation and has standard external measurements of 3U.

Thermal isolation is POROGEL Medium Spaceloft material, 6 mm thick. It is composed of fibreglass and silica aerogel, which makes its thermal conductivity very low – thermal properties are as good as for other, significantly thicker, materials (Aspen Aerogels Inc. 2009, *URSA – Produkty* 2018).

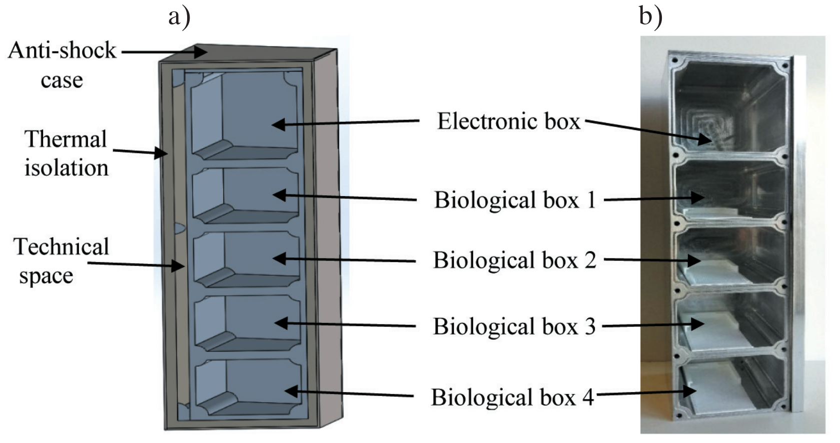

Fig. 1. Section through the model of rocket payload *BeeO!Logical* (2nd iteration) with marked main parts (a) and photograph of actual payload with marked boxes locations (b)

In the second iteration of the device, electronic and biological boxes were milled from one aluminium block, lowering significantly the possibility of a leak which could affect data about CO_2 negatively. The biggest is the electronic box. It is part where the onboard computer and power source is stored. Lower are four biological boxes where honeybees (queens with attendants or drones) are placed. Bees are delivered from the apiary in queen mailing cages, a standard container in which bees are transported (Fig. 2).

Fig. 2. Queen mailing cages. Queens (marked with white dots) and their attendants are visible inside

Dedicated, 3D-printed holders inside biological boxes (white objects on the photograph on the right side of Figure 1) simplify safe montage of cages and exclude the necessity of additional specimens' relocation, lowering the impact of additional stress which could affect results. It also allows to easily mark the samples. That shortens the time needed for payload assembly which ensures maximum limiting bees' stress.

Payload is equipped with suitable sensors which can be divided into two main groups:

1) basic experiment's parameters sensors:
   – temperature sensor,
   – humidity sensor,
   – pressure sensor,
   – vibrometer,
   – accelerometer,
2) vital signs sensors:
   – carbon dioxide sensor,
   – oxygen sensor,
   – on-board camera,
   – lightning system.

The first group of sensors measures all important parameters of the experiment inside the payload. They are placed in the electronic box, along with the onboard computer and power supply, except temperature and humidity sensor, which are build-in devices in the CO_2 sensor. Such location enables to establish if the basic internal parameters are harmless for honeybees.

Vital signs sensors were placed in one of four biological boxes. They measured parameters important from the point of view of a living organism. Gas sensors were used to ensure that air composition stays stable and is not poisonous. Especially important was the CO_2 sensor as too high concentration of this gas causes specimens' anaesthesia. It was proven that such hibernation type shortens honeybees' lifespan significantly (Eskov et al. 2013, Eskov and Eskova 2015). Measuring this factor was then crucial for the proper interpretation of results. All sensors led measurements for the whole time of the experiment.

3. Experiments

In 2019 two experiments on worker honeybees were made with two different sounding rockets. *BeeO!Logical*'s previous iteration (Stasiowska 2020) was used. The first experiment was done with the 'Carbonara' rocket. The typical G-stress value measured during its launch is 3 G and the apogee of its flight was about 800 m. Assessment of bees' condition was made by observing their behaviour. Specimens from the test sample needed about three times more time to attend the flight after the end of the experiment than those in the control sample.

The second experiment took place in Spaceport America, New Mexico, USA. The rocket, in which the payload was placed, had a malfunction causing shortening and intensification of the flight, hardening the landing, and achieving an apogee of only 225 m. The maximum acceleration was 6.5 G. Six out of eleven specimens survived the flight in the test sample, while in the control sample all bees stayed alive. What is very important is that the same bees were tested for three next days, due to the low availability of bees in the US and their high price in the required season.

All basic data on both experiments and specimens' survivability are shown in Table 1.

Table 1

Basic data about preliminary experiments conducted in sounding rockets

Platform	Place	Date	Maximum G-force value [Gs]	Number of alive specimens				Total enclosing time [min]	Other comments
				before the experiment		after the experiment			
				TS	CS	TS	CS		
Carbonara Rocket	Błędów Desert, Poland	17th May 2019	6.5	17	15	17	15	~60	Specimens from TS needed more time for the first flight attempt. No significant measurements from sensors
PROtotype Rocket	Spaceport America, New Mexico, USA	23rd June 2019	3.0	11	13	6	13	~350	Rocket malfunction. The same specimens used for three days (data from 3rd day)

Source: own study based on data from AGH Space Systems Students' Association

In 2021 preliminary research on *A. mellifera* fertility was done, with the usage of the Human Training Centrifuge. Four artificially inseminated queens were given to the G-force pattern characteristic for the *Soyuz* rocket (Fig. 3), another four were a control sample.

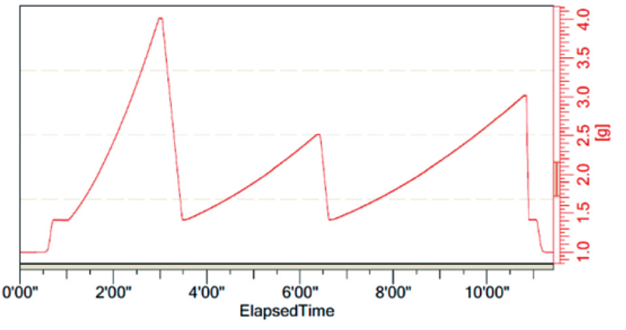

Fig. 3. HTC's experiment's acceleration pattern
Source: MIAM's HTC experiment report

All specimens survived and were given to the professional apiary to be given to colonies. Three out of four queens from each group were accepted. The queen from the tested sample despite the fact of laying eggs was not accepted into the colony. The queen from the control sample was initially accepted but after failing to lay eggs was replaced by the worker bees. One additional queen from the control sample started to lay eggs with significant delay.

The assessment of the queens' fertility was done in experimental beehives, the mini-plus model. Data regarding the share of cells containing food supplies, eggs, larvae and pupae was gathered and is currently under further investigation in order to assess the impact of a G-force on honeybee (*A. mellifera*) queens. The number of eggs laid was recorded and counted (Fig. 4) at regular intervals noted in a dedicated file.

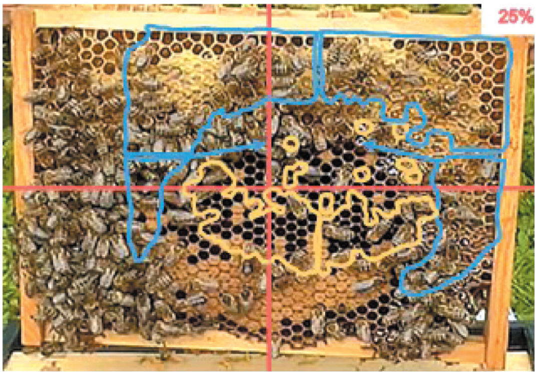

Fig. 4. Eggs/larvae/pupae counting method – frame's area is divided in four, the number is estimated in each quarter and then the resultant is calculated. The process is repeated for each side of all frames

After about a month of the experiment, all colonies were enlarged by additional beehive bodies with workers – such an operation enabled colonies to survive the winter in good condition, however, affected research and disturbed the results. Nevertheless, preliminary results indicate some weak correlation between experiencing G-stress by the queen and the disturbances in reproduction pattern and colony strength. It can be seen in Figure 5, where the change in food stores amount, which is i.a. function of the workers' number, can be seen. The green dotted line indicates the moment of artificial colonies enlargement – it is visible that from this moment amount of food stores is similar for both samples.

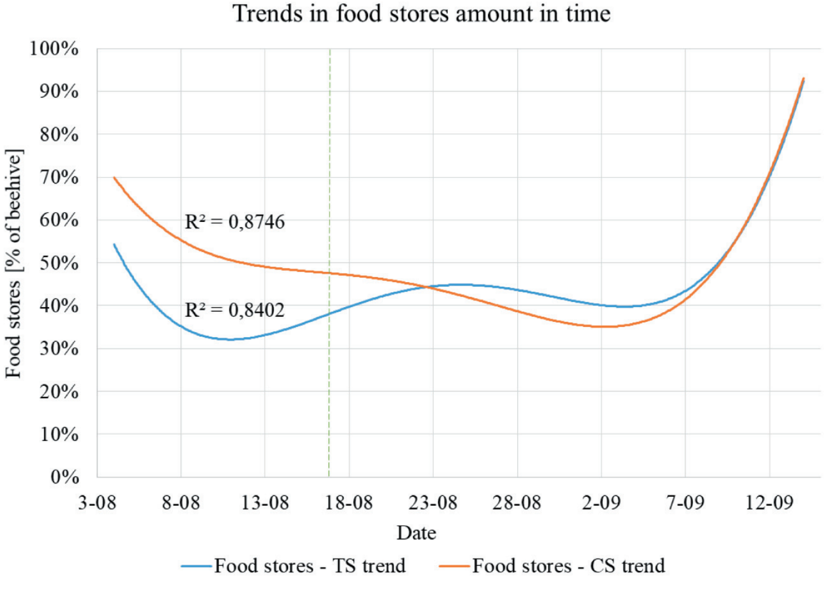

Fig. 5. Trends in food stores amount concerning the whole hive [%]

Nonetheless, to confirm it, it is necessary to deepen the research and enlarge the samples.

Basic information on the acceleration platform, maximum G-force and above-described experiments duration can be seen in Table 2.

Table 2
Preliminary experiments' G-force characteristics

Acceleration platform	Max G-force [G]	Experiment duration [s]
Carbonara sounding rocket	3.0	180
PROtotype sounding rocket	6.5	100
Human Training Centrifuge	4.0	690

Source: own study based on data from the AGH Space Systems Students' Association and Military Institute of Aviation Medicine

4. Future work – computer model implementation

As it is very hard to assess the cause of changes in honeybee queen fertility only based on anatomical and physiological changes, it was decided to conclude this topic by watching its behaviour, i.a. observing the number of laid eggs. Such an approach enables to collect the data that can be transformed and implemented in the simulation. Computer simulation allows controlling all its parameters deciding about observed processes dynamics. By changing parameters it is possible to obtain results characteristic for “G-stressed” queens and to assess their long-term impact on colony development potential.

The most developed model nowadays, available for free, is BEEHAVE (Becher et al. 2014). It is used by some European organisations, such as the European Food Safety Authority EFSA to assess the impact of pesticides on nearby colonies. What is more, the model is easily available (it can be downloaded from the project website) and its whole documentation is public. As the process of full model creation is long and complicated and the most developed model nowadays, BEEHAVE (Becher et al. 2014), is available on the project’s website and can be freely downloaded and used (*BEEHAVE – The Model* 2013), the author decided to expand it and create dedicated modules describing “G-forced” specimens. Predictions correctness of the BEEHAVE has been confirmed multiple times by different scientific groups (Horn et al. 2016, Agatz et al. 2019, Abi-Akar et al. 2020). The model is based on the NetLogo software, making it simple to use while keeping high development possibilities (Tisue and Wilensky 2004). Its predictions’ correctness has been confirmed multiple times by different scientific groups (Horn et al. 2016, Agatz et al. 2019, Abi-Akar et al. 2020). The model bases on the NetLogo software, making it simple to use while keeping high development possibilities (Tisue and Wilensky 2004). For those reasons parameters describing examined colonies will be used to create a new module of a bee colony with G-stressed queens for the BEEHAVE model.

Results of simulation of a colony development with a G-forced queen will be then compared with results achieved for the “normal” colony (control sample). Such a comparison will enable to check the long-term impact of hypergravity on bee colony development. Data about G-stressed queens’ fertility, compared as a separate scenario for each G value, will enable to check which of those values changes the model predictions the most. That will let to assess which value is significantly harmful to the swarm from a long-term perspective and what causes this harmfulness. Exemplary simulation results from the BEEHAVE can be seen in Figure 6.

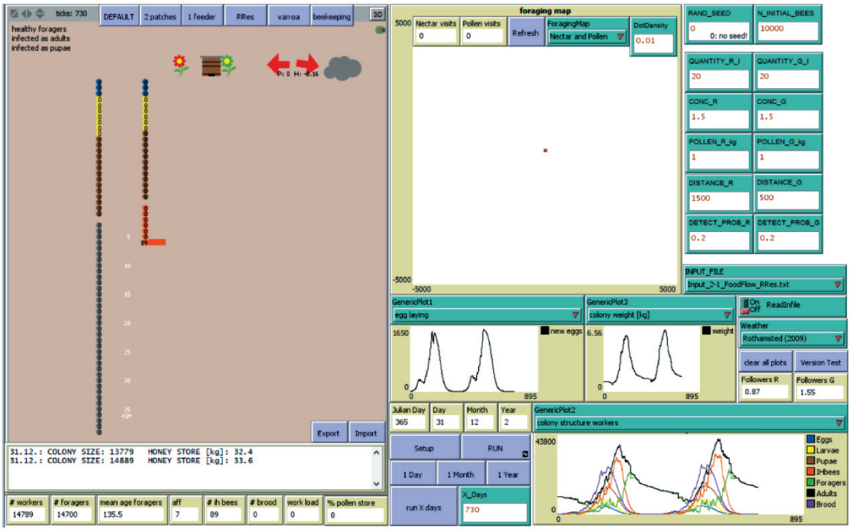

Fig. 6. Exemplary simulation results from the BEEHAVE program
Source: printscreen from the BEEHAVE program

5. Conclusions and future work

Conducted experiments let to suppose that G-stress has an impact on *A. mellifera*, may lower the fertility of queen and in extreme conditions can even cause specimens death. There is a slight difference in the food stores amount between the test and control sample, however, to confirm the negative impact of the G-force there is a need to develop the project further.

After deepened analysis of the data on fertility, the computer model will be developed to assess its usefulness in researched context. If such a module will appear consistent enough it could be transferred to other pollinator species which would significantly accelerate research on pollinators in space travel conditions.

Research was funded by AGH University of Science and Technology (dean's grant 2021 and 2022) and by Apikultura Foundation.

References

Abi-Akar F., Schmolke A., Roy C., Galic N., Hinarejos S., 2020, *Simulating Honey Bee Large-Scale Colony Feeding Studies Using the BEEHAVE Model – Part II: Analysis of Overwintering Outcomes*, Environmental Toxicology and Chemistry, vol. 39(11), pp. 2286–2297. https://doi.org/10.1002/etc.4844.

Agatz A., Kuhl R., Miles M., Schad T., Preuss T.G., 2019, *An Evaluation of the BEEHAVE Model Using Honey Bee Field Study Data: Insights and Recommendations*, Environmental Toxicology and Chemistry, vol. 38(11), pp. 2535–2545. https://doi.org/10.1002/etc.4547.

Anjum F.M., Nadeem M., Khan M.I., Hussain S., 2012, *Nutritional and therapeutic potential of sunflower seeds: A review*, British Food Journal, vol. 114, no. 4, pp. 544–552. https://doi.org/10.1108/00070701211219559.

Aspen Aerogels Inc., 2009. *Karta charakterystyki Spaceloft®*. http://www.aerogels.pl/files/karta_techniczna/porogel_medium%20spaceloft.pdf [access: 15.11.2018].

Becher M.A., Grimm V., Thorbek P., Horn J., Kennedy P.J., Osborne J.L., 2014, *BEEHAVE: a systems model of honeybee colony dynamics and foraging to explore multifactorial causes of colony failure*, Journal of Applied Ecology, vol. 51(2), pp. 470–482. https://doi.org/10.1111/1365-2664.12222.

BEEHAVE – The Model, 2013, https://beehave-model.net/ [access: 5.05.2021].

Elon Musk on Twitter, 2022, *@SpaceHub_SL 2029*, Twitter. https://twitter.com/elonmusk/status/1504173360456077313 [access: 22.03.2022].

Eskov E.K., Eskova M.D., 2015, *The effect of hypoxia on the development of honeybee workers at prepupal and pupal stages*, Journal of Evolutionary Biochemistry and Physiology, vol. 51, pp. 216–221. https://doi.org/10.1134/S0022093015030064.

Eskov E.K., Eskova M.D., Spasik S.E., 2013, *Changes in body mass and life span of honeybee Apis mellifera L. under effect of narcotization with carbon dioxide*, Journal of Evolutionary Biochemistry and Physiology, vol. 49, pp. 627–629. https://doi.org/10.1134/S002209301306011X.

Food and Agriculture Organization of the United Nations (FAO), 2018, *Why bees matter. The importance of bees and other pollinators for food and agriculture*. https://www.worldbeeday.org/files/brosure/FAO_brosura_ENG_print.pdf [access: 18.03.2019].

Glew R.H., Glew R.S., Chuang L.T., Huang Y.S., Millson M., Constans D., Vanderjagt D.J., 2006, *Amino acid, mineral and fatty acid content of pumpkin seeds (Cucurbita spp) and Cyperus esculentus nuts in the Republic of Niger*, Plant Foods for Human Nutrition, vol. 61, pp. 51–56. https://doi.org/10.1007/s11130-006-0010-z.

Horn J., Becher M.A., Kennedy P.J., Osborne J.L., Grimm V., 2016, *Multiple stressors: using the honeybee model BEEHAVE to explore how spatial and temporal forage stress affects colony resilience*, Oikos, vol. 125(7), pp. 1001–1016. https://doi.org/10.1111/oik.02636.

National Aeronautics and Space Administration (NASA), 2020, *Artemis Plan – NASA's Lunar Exploration Program Overview*. https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf [access: 29.10.2021].

Onboard STS-3, 1982, NASA Report to Educators, vol. 10, no. 1, pp. 1–4. https://play.google.com/books/reader?id=5ApkxWlHWsYC&pg=GBS.RA2-PA8&hl=pl [access: 13.05.2020].

Petraru A., Ursachi F., Amariei S., 2021, *Nutritional Characteristics Assessment of Sunflower Seeds, Oil and Cake. Perspective of Using Sunflower Oilcakes as a Functional Ingredient*, Plants, vol. 10(11), 2487. https://doi.org/10.3390/plants10112487.

Space Shuttle – Mission Archives – STS-107, 2003, National Aeronautics and Space Administration. https://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-107.html [access: 13.05.2020].

Space Shuttle Launch Motion Analysis, 2011, National Aeronautics and Space Administration. https://www.nasa.gov/audience/foreducators/mathandscience/controlcenter/Prob_SSLaunchMotion_detail.html [access: 13.05.2020].

Stasiowska D., 2020, *Can we be with Bee on Mars? Evaluating the Impact of a Rocket Flight on the Condition of Honeybees (Apis mellifera)*, Transactions on Aerospace Research, vol. 2020, no. 2, pp. 36–46. https://doi.org/10.2478/tar-2020-0009.

Tisue S., Wilensky U., 2004, *NetLogo: A Simple Environment for Modeling Complexity* [paper presentation], International Conference on Complex Systems, Boston, May 16–21, 2004.

URSA – Produkty, 2018, URSA Polska Sp. z o.o. https://www.ursa.pl/produkty [access: 13.05.2020].

Vandenberg J.D., Massie D.R., Shimanuki H., Peterson J.R., Poskevich D.M., 1985, *Survival, behavior and comb construction by honey bees, Apis mellifera, in zero gravity aboard NASA shuttle mission STS-13*, Apidologie, vol. 16, no. 4, pp. 369–384. https://doi.org/10.1051/apido:19850402.

Wietzke A., Westphal C., Gras P., Kraft M., Pfohl K., Karlovsky P., Pawelzik E., Tscharntke T., Smit I., 2018, *Insect pollination as a key factor for strawberry physiology and marketable fruit quality*, Agriculture, Ecosystems & Environment, vol. 258, pp. 197–204. https://doi.org/10.1016/j.agee.2018.01.036.