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Enemies and allies: the different roles of insects towards fruit and vegetable loss and waste

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Abstract: The halving of food loss and waste is one of the 2030 Agenda main goals. For fruit and vegetables, loss and waste occur from the field to the table, reaching worldwide around 572 million tonnes per year. One of the major causes of damages and spoilage is represented by insect pests. In the Mediterranean area, the most threatening species at the post-harvest and storage stages are *Ceratitis capitata*, *Drosophila suzukii*, and *Spodoptera littoralis*. On the other hand, some valuable insects like *Hermetia illucens* can bioconvert organic by-products and waste into upcycled materials (e.g., lipids, proteins, biofuels) and be a source of chitosan. Chitosan can be applied as a protectant of fruit and vegetables against pests and pathogens. This report includes some notes about the damages caused by the selected insect pests and the useful applications of *H. illucens*. Furthermore, we summarise the involvement of the entomology laboratory of the Department of Agriculture, Food and Environment of the University of Pisa in loss and waste of fruit and vegetable management.

Introduction

Among the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda, Target 12.3 of the SDG 12 "Ensure sustainable consumption and production patterns" calls to reduce the global food loss and waste rates all along the production chain by 2030 (UN, 2015). The share of food grown for human consumption lost or wasted reaches every year worldwide more than 33% of the produced goods, quantifiable in a shocking 1.3 billion tonnes and 835 billion € (FAO, 2001). Food losses are related to accidents along the supply chain, due to environmental, technological, infrastructural, or managerial failures before reaching the retailers. Food waste, instead, occurs at the retail stores and points of consumption (homes, restaurants, eating establishments) when food is

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discarded because it does not meet the desired criteria of maturity, taste, appearance, or expiry date (FAO, 2017). Food losses during handling and storage are the most common in low-income regions such as Sub-Saharan Africa (36% of production in tonnes) and South and Southeast Asia (33%). Food wastes in shops, households, and restaurants are characteristic of medium and high-income regions, primarily North America and Oceania (58%), followed by Europe (42%). Production losses in the field are usual, instead, in all the regions (21 to 36%) (Flanagan et al., 2019).

The reduction of food loss and waste by 50% could help to sustainably feed the world population (expected to reach 9.73 billion people by 2050), lower greenhouse gases emissions, and avoid the conversion of further natural ecosystems into agricultural lands. Furthermore, all the expected positive outcomes would meet the goals of other 2030 Agenda SDGs about health, climate, land, and water quality improvements (UN, 2015).

When considering the weight, the largest share (44%) of the 1.3 billion tonnes of food globally lost or wasted during a year is represented by fruits and vegetables (13% in terms of calories, because of the high content in water). The hotspots of loss and waste for this commodity group are all along the supply chain stages, from production to handling, storage, distribution, market, and consumption (Flanagan et al., 2019). The causes are due to biotic (insect pests, mites, rodents, pathogens, weeds) and abiotic factors (temperature, humidity, and weather in the field and during the path up to the final consumers).

Limiting this evaluation to the post-harvest and storage stages, the key insect species that threaten fruit and vegetable in the Mediterranean area are three. Among the Diptera, we included in this report the fruit fly *Ceratitis capitata* (Tephritidae) related to the damages on citrus fruits and more than 260 other plants and the invasive *Drosophila suzukii* (Drosophilidae) that attacks stone fruits and berries. As one of the main pests of vegetables, we considered the Lepidoptera *Spodoptera littoralis* (Noctuidae). Anyhow, many herbivorous and detritivores insects bioconvert food waste into fertilizers and can be used for the extraction of several useful products (e.g., lipids, proteins, biofuels, chitin). Chitin can be chemically converted into chitosan (CHT), a polysaccharide that is recently gaining more and more visibility as a compound used in the packaging industry (Morin-Crini et al., 2019). In this regard, the most studied and valued species is *Hermetia illucens* (Diptera: Stratiomyidae) (Fowles and Nansen, 2020). This contribution also includes an overview of the activities related to food loss reduction and waste management carried out at the entomology laboratory of the Department of Agriculture, Food and Environment (DAFE) of the University of Pisa.

Insect pests of fruit and vegetables in the Mediterranean area

The most destructive insect pests at the post-harvest and storage stages in the Mediterranean area are *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) and *Drosophila suzukii* (Matsumura, 1931) (Diptera: Drosophilidae) for fruits and *Spodoptera littoralis* (Boisduval, 1833) (Lepidoptera: Noctuidae) for vegetables. Adults of the three species lay eggs when fruits are immature. During the ripening, the eggs hatch and the emerged larvae voraciously feed on the fruit pulp generating losses in the field. The related marks, lumps, depressions, and abnormalities worsen in the post-harvest and storage stages, making the remaining fruits unsellable and producing waste. It is extremely difficult to calculate the economic value of the amount of fruit and vegetables destructed by the three pests in the Mediterranean area and the rest of the countries where the species are spread. Besides the economic impact due to the decreased production, the high cost for the implementation of control or eradication strategies must be considered (Hosny et al., 1986; Knapp et al., 2021; Papadopoulos, 2014).

Ceratitis capitata, commonly known as the Mediterranean fruit fly or medfly, is endemic to sub-Saharan countries, but it is currently spread throughout the whole African continent, Southern Europe, the Middle East, and Central and South America because of multiple accidental introductions (CABI, 2021a). The species is extremely polyphagous and attacks more than 260 fruits, vegetables, and nuts subtropical and tropical species. The damaged crops of major economic value are apples, apricots, aubergines, avocados, cherries, different citrus varieties, figs, kiwifruits, mangoes, peaches, pears, peppers, and tomatoes. Due to its high tolerance of a wide temperature range and hosts, dispersive ability, short generation time, and invasiveness, the medfly is a European and Mediterranean Plant Protection Organization (EPPO) A2 quarantine pest. Females insert groups of 1 to 10 eggs under the skin of the host fruits at the beginning of the ripening process, using the short ovipositor. In its lifespan, a single female can oviposit up to 800 eggs. After 1.5 to 3 days, the newly hatched larvae feed on the fleshy and sugary fruit tissues (Thomas et al., 2001). In addition to the direct damage, the eaten goods face rotting by secondary bacteria and fungi attacks.

Drosophila suzukii, also known as the spotted wing drosophila, is a fruit fly native to East and Southeast Asia, now present in all the European, American, and Asian continents due to global trade (CABI, 2021b). The species is one of the main threats to stone fruits and berries, among which the most economically relevant are apricots, blackberries, blueberries, cherries, grapes, nectarines, peaches, pears, plums, raspberries, and strawberries. Because of its wide range of hosts, wild species included, the high reproductive rate, and short biological cycle, *D. suzukii* is recorded in the EPPO alert list. Females usually lay one single egg at a time below the soft skin of ripening fruits by using their long, serrated ovipositor. Each female can oviposit up to 500 eggs in its lifespan (Lee et al., 2011). According to the temperature, larvae hatch in a few days and grow inside the host fruits, destroying them. As reported for *C. capitata*, the attacked fruits may be subjected to infections by secondary pathogens too.

Spodoptera littoralis is a moth commonly called the African cotton leafworm. Its distribution area includes Africa, Mediterranean Europe, China, and India; the origin of the species traces back to Africa (CABI, 2021c). *S. littoralis* is highly polyphagous and attacks at least 87 cultivated and crops species. As suggested by its common name, cotton is the most threatened crop, but beets, bell peppers, cabbage, carrots, corn, eggplants, lettuce, onions, peas, potatoes, soybeans, spinach, tomatoes, and sunflowers are severely damaged too. For these reasons, the species is listed as an A2 quarantine pest by EPPO. Females lay masses of 20 to 1000 eggs, preferably on the abaxial surface of young leaves. The emerged larvae feed on the young leaves, shoots, stalks, buds, flowers, and fruits, creating large holes that make the commercial attacked goods unsuitable for consumption (Sullivan, 2007).

The contribution of insects to the fruit and vegetable loss and waste management

Several herbivorous and detritivores insect species (e.g., crickets, mealworms and houseflies' larvae) are reported to be able to bioconvert organic materials into fertilizers and can be used for the extraction of several useful commodities (e.g., lipids, proteins, biofuels, chitin). Among these species, *Hermetia illucens* (Linnaeus, 1758) (Diptera: Stratiomyidae), also known as the black soldier fly, is the most studied and valued candidate (Fowles and Nansen, 2020). This fly originates from the South American temperate zone, but it is becoming cosmopolitan. When mass-reared, females lay 206 to 639 eggs in the organic matter provided. After the hatching, larvae feed voraciously on the substrate and digest daily more than twice their weight. Under ideal conditions of temperature and humidity, the bioconversion process carried out by the larvae lasts about two weeks, then they pupate far from the damp food source (Tomberlin et al., 2002). Through different chemical and industrial processes, the black soldier fly prepupae and pupae can be transformed into livestock, poultry, and aquaculture feed (as they are or as lipid and protein supplements), biodiesel, and biogas (Singh and Kumari, 2019). Another distinctive feature of *H. illucens* is the high content in chitin, up to 24% (Soetemans et al., 2020). From chitin, through deacetylation, it is possible to obtain CHT, a linear polysaccharide composed of β-(1,4)-linked-D-glucosamine and N-acetyl-D-glucosamine units. CHT is already widely employed in agriculture, medicine, food preservation, and the packaging industry (Morin-Crini et al., 2019).

The involvement of the entomology laboratory of the DAFE of the University of Pisa

The project Fedkito (FrEsh FooD sustainable pacKaging in the cIrcular economy), funded by the PRIMA (Partnership on Research and Innovation in the Mediterranean Area) Foundation and the Italian Ministero dell'Università e della Ricerca, is coordinated by the DAFE of the University of Pisa. Fedkito started on the 15th of September 2020 and will end on the 14th of September 2023. It involves entomologists, mycologists, chemists, sensory analysts, material engineers, fresh food producers, economists, and data analysts, following a multidisciplinary approach. Fedkito consortium includes three European countries (Italy, France, and Greece) and two third countries (Morocco and Tunisia). The overall goal of the project is to reduce the waste of perishable fresh food: first, prolonging the products shelf-life using CHT and essential oils (EOs) formulated in innovative packaging solutions and secondly, using the fresh food by-products and waste to mass rear *H. illucens*, then employed to produce CHT under a circular economy approach.

In the detail, *H. illucens* is currently reared at the DAFE and the University of Thessaly on fresh food waste derived from the selection for the market, supplied by local retailers. Once obtained, the pupae are chemically processed by the DAFE chemists to extract first chitin, then CHT. Different dietary compositions are under evaluation to better valorise the waste and achieve a higher amount of chitin in the pupal cuticle.

To a standard artificial diet, variables percentages of fruits only (apples, bananas, and oranges), vegetables only (celery, bell peppers, and potatoes), protein-based ingredients from dairy and meat, or mixtures of the three groups are added. In the meantime, the protection given by a coating of commercial CHT extracted from crab shells, with or without some selected EOs, is tested against the oviposition and attack of *C. capitata* on kumquats and peaches, *D. suzukii* on blueberries and cherries, and *S. littoralis* on tomatoes, both at the DAFE and the Sorbonne Université. The same trials will be then repeated using the black soldier fly CHT, and the results will be compared to those previously obtained with the commercial product.

Furthermore, within the Fedkito project, the DAFE expert panellists selected the most suitable EOs, in terms of odour and flavour (Farina et al., 2021), to be used with CHT for fruit and vegetable protection. The DAFE mycologists will use the chosen EOs and CHT to assess the growth, spore germination, and sporulation of *Penicillium digitatum*, *P. expansum*, and *P. italicum*, agents of moulds in apples and citrus fruits. The Technical Center Industriel de la Plasturgie et des Composites will use CHT and the specified EOs to create a new matrix extrudable as a film. In such film, low-cost and easy to use biosensors to detect mycotoxins, pesticides residues, microbial contaminants, temperature fluctuations, and quality characteristics of fruit and vegetables, developed by the University of Bologna and Université Hassan II de Casablanca, will be embedded. The Centre de Biotechnologie de Borj Cédria will then focus on the impact of the novel technologies on the quantitative and qualitative nutritional properties of the food over time. Lastly, a socio-economic analysis of the innovative solutions proposed within Fedkito will be performed, counting on participatory workshops helpful to stimulate the interaction among scientists, stakeholders, and end-users.

Conclusions

Despite the chemical and green pesticides, biological control, and pheromones application, the *C. capitata*, *D. suzukii*, and *S. littoralis* management has not been conclusive yet. Therefore, the loss and waste of fruit and vegetables caused by these species and a very high number of other pests needs to be reduced by implementing new approaches. One solution to contain the post-harvest losses could be the treatment of fruit and vegetables with CHT formulations (spray, fluid, film) possibly enriched with EOs. To valorise the waste, instead, could be advantageous to rear on them *H. illucens*, then used to produce CHT through chemical treatments of its pupae, according to the circular economy criteria. Such proposals are under investigation as part of the PRIMA project Fedkito, coordinated by the DAFE of the University of Pisa. Everyone in the food system, from producers to consumers, including the researchers, have a significant role in this expected reduction of food loss and waste and are strongly requested to get involved.

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