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Review Article

Entomophagy and human food security

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Abstract. Food security is a problem in many developing and less developed countries due to increase in human population and decrease in crop productivity and food availability. Edible insects are a natural renewable resource of food providing carbohydrates, proteins, fats, minerals and vitamins. As such, entomophagy is common in ethnic groups in South America, Mexico, Africa and Asia, where indigenous insects are easily available and are consumed in various forms (raw/processed) or used as an ingredient or supplement in modern recipes. Entomophagy therefore offers an opportunity to bridge the protein gap of human foods irrespective of a few constraints that are discussed. Concerning food security, more attention is needed to assess and revalidate entomophagy in the context of modern life. Further research would be necessary to exploit insect biodiversity and ethno-entomophagy, stop overexploitation of these insects, and initiate actions for insect conservation.

Key words: insect collection, food security, nutritive value, ethnic traditions, commercialization, consumers' awareness

Introduction

Food security is fast becoming a problem for human beings because of booming populations, increase in consumption growth and possible decline in food availability. The productivity of agricultural crops is nearly stagnant and chronic malnutrition is rampant in many poor nations. Natural factors such as climate change, energy crisis, decreasing soil fertility, incidence of pests and plant diseases, and man-made situations such as increased food prices, non-availability of foods, lack of purchasing power of consumers, disparity in food distribution, and so on seem to be responsible for food insecurity (Gahukar, 2009, 2011; Kumar, 2010), while global demand for food will increase for at least another 40 years. For example, by 2030, with the human population rising by six million every month and with current food reserves at a 50-year low, the demand for food will increase by 50% (Beddington, 2010). Searching for new available sources to substitute food can be a viable and requisite step. Likewise, efforts for improving food supply through new technologies would take some time for their application on a large scale to make them feasible/practical, cost-effective and ecofriendly (e.g. genetically modified crops; geo-engineering; crop genotypes with resistance to pests, diseases and drought; plants with the capacity of reflecting sunlight (albedo effect); new chemical molecules; integrated plant nutrient and pest management techniques, etc.). As a global responsibility, at least for member countries, the Food and Agriculture Organization (FAO) of the United Nations took an initiative to create a policy and proposed the programme of feeding people with alternative sources including insects (FAO, 2010*a*,*b*). The organization stresses both physical and economic

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access to food that meets people's needs as well as their preference, even though the globalization of the world economy can affect food security especially in Africa (Kent, 2002).

Entomophagy is the term used to describe the process of eating insects as food. Although 'micro-livestock/mini-livestock' are not equivalent words to entomophagy, they are sometimes used to categorize the insects that can be eaten by human beings (Paoletti and Dufour, 2002; Paoletti, 2005; Srivastava *et al.*, 2009). At present, edible insects are a natural food resource to many ethnic groups in Asia, Africa, Mexico and South America where entomophagy can be sustainable and has economic, nutritional and ecological benefits for rural communities. However, entomophagy is becoming uncommon in some regions due to increasing adoption of modern foods, changed social structures and changes in demography (Yen, 2010). Preference of edible insect species differs as per taste, nutritional value, ethnic customs, local prohibition, family background and easy availability (van Huis, 2003). Ramos-Elorduy (1997*a*) reported 1391 insect species eaten worldwide. Later, the same author reported 1681 species in 14 insect orders (Ramos-Elorduy, 2005) and recently, 2086 insect species that are consumed by 3071 ethnic groups in 130 countries (Ramos-Elorduy, 2009). Likewise, the number of edible insects differs in a region and countries within a region, namely 348 species in Mexico (Ramos-Elorduy, 1997*b*), 250 species in sub-Saharan Africa (van Huis, 2003), 187 species in China (Chen *et al.*, 2009), 96 species in the Central African Republic (Roulon-Doko, 1998), 83 species in Ecuador (Onore, 1997), 60 species in India (Chakravorty, 2009) and Borneo (Chung *et al.*, 2001), 55 species in Japan (Nonaka, 2005), 50 species in Thailand (Yhoung-aree *et al.*, 1997) and 40 species in Nigeria (Banjo *et al.*, 2006*a*). Although different figures are available for different insect orders, the majority of edible insects belong to Lepidoptera, Orthoptera, Coleoptera and Hymenoptera. Other common insect orders are Isoptera, Homoptera, Heteroptera, Diptera and Odonata (Ramos-Elorduy, 1997*b*, 2005; Van Huis, 2003).

Worldwide, entomophagy plays a major role in human food security and has already been reviewed by Illgner and Nel (2000), Craig and Bunn (2001), Morris (2004), Nonaka (2005), Bukkens (2005), and recently by Raffles (2010). Likewise, best sources of information on edible insects are the proceedings of the FAO workshop (FAO, 2010*b*) and 'The Food Insects Newsletter' which is no longer published but a compilation of 13 volumes in a book can be referred to (DeFoliart et al. 2009). In future, there is need of improved nutrition and food security. Thus, considering entomophagy as one of the practical and viable solutions to food security, this review presents recent developments to provide supplementary information to earlier reports, discusses major challenges and envisages future steps in order to feed people by suggesting to include entomophagy in future food security plans and initiatives.

Why entomophagy?

Entomophagy is practised generally for the following reasons:

(1) Insects are found easily in forestland and water resources and can be mass-collected in a short time whenever their populations are abundant.

(2) Insects can be reared and multiplied easily in small spaces and a short period due to their short life cycle and high intrinsic growth rate. Edible insects need not be fed on grains so rearing is more environmentally friendly than traditional livestock (Oonincx *et al.*, 2010). Insects reproduce faster than traditional livestock. For example, the female house cricket *Acheta domesticus* L. (Orthoptera: Gryllidae) can lay from 1200 to 1500 eggs in 3–4 weeks and its water requirement is very low, while for beef, the ratio is four breeding animals for each animal marketed (Capinera, 2004). Further, the efficiency of conversion of ingested food (ECI) is higher (up to 44% in some insects) than for traditional meats (Gordon, 1998; Callavo *et al.*, 2005; Chakravorty, 2009). For instance, the house cricket has an ECI twice as efficient as pigs and broiler chickens, four times greater than that of sheep and six times higher than a steer when losses in carcass trim and dressing percentage are accounted for (Capinera, 2004).

(3) In low-income areas, only insects are available in the period of food shortage, particularly at the beginning of the rainy season when livestock is lean, new crops have just been sown and the stocks of stored produce from the previous crop season become limited. Consequently, local markets are flooded with insects packed in plastic bags and sold as food articles during the planting season (Yen, 2009*a*). Similarly, in case of natural disasters (floods, droughts, epidemics of human diseases), ethnic clashes and wars, packets of insects can be easily distributed as an emergency food security measure.

(4) Insects are mostly mixed with, or often consumed as, supplement to predominant diets based on maize, cassava, sorghum, millet, beans and rice, and form an ingredient to produce other food items (Bukkens, 2005). In Mexico, a 'tortilla' (a thin flat bread made from finely ground maize) is supplemented with ground mealworm (*Tenebrio molitor* L. (Coleoptera: Tenebrionidae)) larvae (Aguilar-Miranda *et al.*, 2002), whereas the termite *Microtermes bellicosus* Smeathman (Isoptera: Termitidae: Macrotermitinae) supplements maize protein alone in Nigeria (Bukkens, 1997).

(5) Insect preparations include frying, braising, stewing, stewing after frying, boiling and roasting. Eggs to adults are eaten but larvae and pupae are regularly sold in restaurants, and local and retail markets in urban areas (Chen *et al.*, 2009). For example, fried grasshoppers in cans and chocolate-covered ants are sold in Mexico, chocolate chirpy chips or popcorn with roasted crickets and grasshoppers (known as chapulines) in the USA, ants with popcorn in Colombia and maggot cheese in Italy are a local delicacy (Capinera, 2004; Kittler and Sucher, 2008). Some restaurants in the USA are incorporating insects into their recipe books and menus such as stir-fried mealworms and caterpillar crunch (a combination of trail mix and fried caterpillars; Capinera, 2004; Gracer, 2010).

(6) Apart from local markets, export of insects in the form of beetle juice, canned silkworm pupae, caterpillars of hesperid butterflies and immature stages of ants has been initiated by the food industries in developed countries (Ramos-Elorduy, 1998).

(7) Entomophagy had been used regularly by tribes for centuries as medical treatments and the same practice is being continued in certain countries (Fosaranti, 1997; Pemberton, 1999; Costa-Neto, 2000; Chung *et al.*, 2001; Padmanabhan and Sujana, 2008; Feng *et al.*, 2009; Srivastava *et al.*, 2009; Chakravorty *et al.*, 2011). Ayieko and Oriaro (2008) reported that lake flies (*Chaoborus* spp. (Diptera: Chaoboridae) and *Chironomus* spp. (Diptera: Chironomidae)) are fed to weak children with 'insect biscuits' to gain strength.

(8) Insects produce much smaller quantities of greenhouse gases (GHG, particularly methane and nitrous oxide) per kilogram of meat than conventional livestock (Oonicx *et al.*, 2010). A pig produces up to 100 times more GHG compared with mealworms. Emission of ammonia, which causes the acidification and eutrophication of ground water, also appears to be significantly lower. A pig produces 8–12 times more ammonia compared with crickets and up to 50 times more than locusts (Ooincx *et al.*, 2010).

Nutritive value of insects

Apart from the reasons mentioned above, insects have been well recognized worldwide as nutritious food since insects provide proteins (amino acids including methionine, cysteine, lysine, and threonine), carbohydrates, fats, some minerals and vitamins, and have energy value (Capinera, 2004; Johnson, 2010; Xiaoming *et al.*, 2010). For example, caterpillars contain proteins to the extent of 50–60 g/100 g dry weight, the palm weevil grubs contain 23–36 g, Orthoptera contain 41–91 g, ants contain 7–25 g and termites contain 35–65 g/100 g (Bukkens, 1997; Ramos-Elorduy, 2005). This quantity is more than in ground beef (27.4 g) or broiled cod fish (28.5 g) (Banjo *et al.*, 2006*a*; Okaraonye and Ikewuchi, 2008). Maximum contents of 100 g amino acids/100 g dry weight of silkworms' pupae followed by the bamboo caterpillar *Omphisa fuscidentalis* Hmps. (Lepidoptera: Crambidae) (77.5 g) and the house cricket (68.7 g) have been reported (Yhoung-aree, 2010). Caterpillars, grubs of palm weevils (*Rhynchophorus* spp. (Coleoptera: Curculionidae)) and termites are rich in fat (Bukkens, 1997). Maximum contents of calcium of 61.3, 72.4 and 76 g/100 g dry weight have been recorded, respectively, in dung beetle (*Oryctes* sp. (Coleoptera: Scarabaeidae)) grubs (Banjo *et al.*, 2006*a*), palm weevil grubs (Onzikou *et al.*, 2010) and adult house crickets (Vogel, 2010). Maximum contents of iron of 27–29 and 35.5 g/100 g dry weight have been found in termites and caterpillars, respectively (Banjo *et al.*, 2006*a*). Similarly, maximum contents of phosphorus of 226–238 g/100 g are present in grasshoppers and the giant water bug *Lethocerus indicus* Lepeletier & Seville (Hemiptera: Belostomatidae; Feng *et al.*, 2000). A high content of magnesium (7.54–8.21 g/100 g) has been found in grasshoppers and weevils (Banjo *et al.*, 2006*a*). Eggs, larvae and pupae of honeybees have a high amount of vitamins A, B_2 and C to the extent of 12.44 μg/100 g, 3.24 mg/100 g and 10.25 mg/100 g, respectively (Bukkens, 1997). Calories obtainable from insects run as high as 776.9 kcal/100 g of insects, often exceeding those from soybean, maize and beef (Ramos-Elorduy, 2005).

A bread containing grubs of the African palm weevil *Rhynchophorus phoenicis* (F.) provides the major and minor nutrients essential for body growth (Ekpo and Onigbinde, 2005). In a recent study in Kenya, wheat buns enriched (5% mix) with the termite *Macrotermes subhyalinus* Rambur (Isoptera: Termitidae) were better than ordinary breads for some attributes (e.g. size, colour, texture, aroma) and consumers' preference. Further, Kinyuru *et al.* (2009) found higher contents of riboflavin (0.17 *versus* 0.26 mg), niacin (0.90 *versus* 1.11 mg), folic acid (0.30 *versus* 0.33 mg), calcium (10 *versus* 10.83 mg), iron (1.20 *versus* 1.80 mg) and zinc (2.78 *versus* 3.23 mg) than in ordinary bread. The oil extracted from *R. phoenicis* grubs contains a high level of unsaturated components and exhibits good physiological properties due to which it is used as edible oil (Okaraonye and Ikewuchi, 2008; Onzikou *et al.*, 2010). In the case of silkworm caterpillars, eating them can be sufficient for daily requirements of copper, zinc, iron, thiamin and riboflavin, and the deficiency of riboflavin can be fulfilled by eating those insects containing this amino acid (Gordon, 1998). Protein production from insects is also ecologically sustainable and consumes fewer resources than animal protein (Gordon, 1998). Further research is needed to ascertain whether the production of a kilogram of insect protein is also more environmentally friendly than conventional animal protein when the entire production chain is taken into account.

Recent developments in insect collection

Techniques and entomophagy

Coleoptera

The grubs of *R. phoenicis* and the coconut rhinoceros beetles *Oryctes rhinoceros* L. and *O. boas* F. (Scarabaeidae) are a common food in the Democratic Republic of Congo (DRC) (Onyeike *et al.*, 2005; Onzikou *et al.*, 2010) and Nigeria (Ekpo and Onigbinde, 2005). Dung beetles including *Heliocopris bucephalus* F. (Scarabaeidae) are collected generally in the morning by digging them out from cattle dung, placed into a container filled with water to soak for 12 h or until no more food remains in their intestines before they can be cooked (Hanboonsong, 2010). In the Philippines, grubs of June beetle, *Phyllophaga* spp. (Scarabaeidae), are fried, stewed, grilled or roasted and often condiments including onions, pepper and salt are added. Dried grubs are often incorporated into a paste and clarified fat is used as butter (Adalla and Cervancia, 2010). Frying (after removing the gut content) of the red palm weevil grub/sago grub *Rhynchophorus ferrugineus* and the scarabaeid *Chalcosoma atlas* L. (Scarabaeidae) is common in Java (Lukiwati, 2010), whereas the most common edible insect in Papua (Indonesia) is the black palm weevil *R. bilineatus* Montrouzier. Grubs are generally consumed raw or after some roasting (Ramandey and Mastrigt, 2010). Similarly, cetonid beetles (*Cotilis* spp. (Cetoniidae)) and cerambycid beetles (*Rosenbergia mandibularis* Ritsema (Cerambycidae)) resting on tall flowering trees are collected, skewered on a small stick and roasted. The longicorn beetle *Batocera wallacei* Thomson (Cerambycidae) is roasted, often before removing the legs and wing casings and consuming the fat-filled abdomen (Chung, 2010; Ramandey and Mastrigt, 2010). The sago grubs (collected from sago plants) are used as porridge with thin slices of ginger or they are stir-fried with soybean sauce and shallots (Chung, 2010). Exceptionally, the eggs of the stick insect *Haaniella grayii grayii* (Westwood) (Phasmatodea: Heteropterygidae) are eaten as a delicacy in Borneo (Chung, 2010).

In the Kalahari region in South Africa, the San people collect the beetle *Sternocera orissa* Buquet (Buprestidae) during its outbreaks. The quarry is roasted in hot ash and sand, and hind wings are removed before being consumed. The heads are picked off if they are eaten directly. Often, powder is prepared and mixed with fruits or leaves of wild plants to form a paste (Nonaka, 1996; van Huis, 2003). Tribes in the Central African Republic relish the grubs of cerambycids and dung beetles, which are searched for near the roots of banana plants or collected near tree trunks (Roulon-Doko, 1998).

Diptera

Lake flies, *Chaoborus edulis* Edwards, *Chaoborus* spp. (Chaoboridae) rise like clouds from Lake Victoria in East Africa. Natives sweep them off from bushes and rocks and collect them by whirling baskets. Cake is prepared by grinding the flies, which is then sun-dried (van Huis, 2003).

Heteroptera

Collecting water bugs around lights at night near water sources is an age-old practice in Mexico where bug eggs are well known for their taste. Two rice bugs, *Leptocorisa oratorius* F. (Coreidae) and *Nezara viridula* L. (Pentatomidae), are relished by farmers in Borneo. They mash the bugs with chillies and salt and cook them in hollow bamboo stems. The dish is served as a condiment (Chung, 2010). In China, the giant water bug *L. indicus* is roasted and eaten whole or ground into a paste with chillies before eating (Feng *et al.*, 2000). In Sudan, the millet bug *Agonoscelis versicolor* F. (Pentatomidae) is roasted and consumed. Also, oil made from these bugs is used in food preparations (Van Huis, 2003).

Homoptera

In Papua (Indonesia) and Borneo, green and brown cicadas (Cicadidae) including *Cosmopsaltria waine* Duffels, *Pomponia merula* Distant, *Orientopsaltria* spp. and *Dundubia* spp. are collected in the morning as adults emerge from the underground pupae (Chung, 2010; Ramandey and Mastrigt, 2010). At night, a fire is set beneath the host trees (such as *Pongamia* spp.), and cicadas eventually drop onto the ground while the tree is being smoked (Chung, 2010). A plastic bag containing some cotton tied to a long stick is used to collect cicadas in Thailand (Hanboonsong, 2010). After removing the wings, they are roasted over an open fire before eating. Sometimes insects are stir-fried with some salt and other flavouring, but always without oil (Chung, 2010).

Hymenoptera

Larvae and pupae (and rarely adults) of honeybees and social wasps are roasted/grilled over a fire and eaten, whereas adult wasps are canned or rice is cooked with wasps or honeybees in Japan, China and Java (Edwards, 1998; Feng *et al.*, 2010). Larvae and pupae of the social honeybee *Apis cerana* F., the giant honeybee *A. dorsata* F., the dwarf honeybee *A. florea* F. and the stingless bee *Trigona biroi* Friese (Apidae) are boiled with porridge or rice, stir-fried or drunk together with honey. Sometimes the brood together with the hive is squeezed to extract liquid which is then boiled (Adalla and Cervancia, 2010; Chung, 2010). In the case of the drury bee *Xylocopa latipes* Drury (Apidae), inhabiting cavities of bamboo or other trees, larvae and pupae are taken from nests and are fried with butter or onion and salt (Lukiwati, 2010). Broods of the wild honeybees are either fried or sautéed with vegetables (Adalla and Cervancia, 2010; Nandasena *et al.*, 2010).

Non-honey food uses in Thailand include capped brood mixed with pollen that is cut into pieces and macerated in alcohol to produce a liquid. Capped brood may also be roasted without pollen and eaten directly (Boongrid, 2010).

Worker wasps are attracted with bait containing a meatball, then the entrance to the nest is disconnected and smoke is generated to sedate the wasps inside the nest. In Japan, some people tie a tiny white ribbon around the waist of the worker wasp while it is eating the bait. Others prefer to collect them at night when the worker wasps are sleeping (Nonaka, 2010). In mountainous areas in Japan, pupae of the common wasp *Vespula flavipes* L., the Asian giant hornet *Vespa mandarinia* Smith, *Vespa* spp. and *Ropalidia* spp. (Vespidae) are boiled with soybean sauce or fried with salt while larvae are boiled to a hard consistency with soybean sauce, sugar and saké. The cooked larvae are then mixed with rice (Chung, 2010; Nonaka, 2010).

Generally, ants are collected by excavating holes in the plants on which ant nests are found. In the Central African Republic, women collect ant eggs by brushing them in a receptacle or by digging the stored eggs out of the nest. Eggs are eaten raw or fried (Roulon-Doko, 1998). In the Kalahari region (South Africa), the San tribe collect ant species of the genus *Camponotus* (Formicidae) by poking a nest with a digging stick and tapping the ground by hand around the nest. The San tribe prepare a powder of wild plants, mix it with ants and add a sweet-sour flavour to the mixture before eating (Nonaka, 1996). Ants fried with butter or onions and garlic are served routinely in the restaurants in China (Luo, 1997). In Malaysia, natives use the giant forest ant *Camponotus gigas* Latreille (Formicidae) as a flavouring because it contains a high concentration of formic acid (Chung, 2010). Eggs of *Camponotus* species are collected from tree trunks without disturbing adult ants and are cooked with spices or sautéed in garlic and onions, and are served in restaurants in the Philippines (Adalla and Cervancia, 2010). In Colombia, the leaf-cutting ant *Atta laevigata* F. Smith (Formicidae) (locally known as 'bachaco') is boiled in salt water and roasted in ceramic pans or ground up to use as a spread on bread (DeFoliart, 1999; Paoletti *et al.*, 2003). In India, eggs are collected from the trees and fried with salt, chillies, spices and mustard oil, and eaten (Srivasatava *et al.*, 2009). People in Mexico keep the immature stages of the tree ant *Liometopum apiculatum* Mayr. (Formicidae) (locally known as 'escamoles' ants) alive for a day before eating. These insects are then fried with onions and garlic or with black butter and served (Ramos-Elorduy, 1997*a*,*b*). Adults of the weaver ant *Oecophylla smaragdina* F. (Formicidae) are mixed with chillies and salt and served as condiments while the brood is eaten raw or cooked with rice or porridge (Chung, 2010).

Isoptera

Large colonies of termites are found in arid and humid areas of Central Africa and Australia. Eating of the queen and the reproductive forms is common globally, whereas soldiers are preferred in Venezuela (Paoletti *et al.*, 2003). Roulon-Doko (1998) and van Huis (2003) reviewed various methods of termite collection in Africa. The most popular and easy way used in the tropics is to collect them during the evening hours by placing a basin of water right under the light source. As light is reflected on the water, termites are attracted and trapped on the water surface (Chung, 2010). The tribes of Africa, especially those in Zambia, the Central African Republic, Angola and the DRC, collect winged sexual forms at the time of nuptial flights of termite species, *Macrotermes falciger* Gerstacker and *M. subhyalinus* (Isoptera: Termitidae), when adults emerge in large numbers from the termitaria after the first rains (Mbata, 1995; Malaisse, 2005). In the DRC, a basket is put upside down over an emergence hole of the mound or a dome-shaped framework of sticks is built up or elephant grass is covered with banana leaves or a blanket to cover part of the emergence hole near which a receptacle is placed to collect flying termites. Continuous beating and drumming on the ground around the hill triggers certain termite species to emerge (van Huis, 2003). To extract soldiers from the mound, women and children push grass blades or parts of tree pods or the bark into the shafts of a termite mound, or prepare smoke from charcoal from certain trees and blow it into the opening; soldiers stripped into a container are then collected. Sometimes nests are dug up to collect queens (van Huis, 2003).

In Africa, termites are eaten raw soon after catching or fried lightly or gently roasted to make them slightly crispy, or smoked/steamed in banana leaves, or simply sun-dried. Oil is not used as termites have a high content of oil in their body. In the DRC and Central African Republic, insects are squeezed or pressed in a tube to form a colourless oil for frying. In Botswana, winged reproductive forms of the harvester termite *Hodotermes mossambicus* Hagen (Hodotermitidae) are roasted in hot ash and sand before being consumed (Nonaka, 1996). In India (Odisha state), termites are eaten as snacks alone or together with rice (Srivasatava *et al.*, 2009). Chinese gulp raw termites with liquor or dip them in alcohol before swallowing (Chung, 2010). Eating raw termites with their wings removed is also common in Borneo (Chung, 2010).

Lepidoptera

Caterpillars of moths and butterflies have been popular dishes in many parts of the world, whereas pupae of the eri silkworm *Samia ricini* Donovan, the Chinese oak silk moth *Antheraea pernyi* Guerin-Meneville and the mulberry silkworm *Bombyx mori* L. (Saturniidae) are consumed by locals in many Asian countries (Zhou and Han, 2006; Sirimungkar-akat *et al.*, 2010; Sarmah, 2011).

In equatorial Africa, natives collect full-grown caterpillars of *Anaphe venata* Butler and *Anaphe* spp. (Thaumetopoeidae), and sell them with cocoons in the local markets (Latham, 1999). When caterpillars of the emperor moths (namely *Imbrasia ertli* Rebel, *Gonimbrasia* (*Imbrasia*) *belina* Westwood, *Cirina forda* Westwood, *Antheua insignata* Gaede and mumpa caterpillar *Gynanisa maja* (Klug) (Saturniidae)) descend from the top to the base of their food plants (often for pupation in the soil), the whole colony is collected. Sometimes fire/smoke is made so that caterpillars drop to the ground. Prior to serving, spines or long hairs on the body are removed or burned off. Caterpillars are then boiled in water or fried with groundnut butter and mixed with cassava leaves, or cooked with pumpkin and sesame seeds, or simply fried with salt and a few hot peppers (Mbata and Chidumayo, 1999; Latham, 2001). Native women in the Kalahari region of South Africa squeeze out the intestines of caterpillars, and roast them in hot ash and sand. They store sun-dried caterpillars in bags for consumption whenever the need arises. For this purpose, dried caterpillars are often pounded into powder and mixed together with stewed watermelon (Nonaka, 1996). In Botswana and South Africa, fourth and fifth instars of the mopani/mopane caterpillar *G. belina* are degutted, cooked in brine and sun-dried to make an edible product and preserved for later consumption or canned for export (Mulhane *et al.*, 2001).

Caterpillars of giant skippers, *Agathymus* spp. and *Megathymus* spp. (Megathymidae), and the hesperid butterfly *Aegiale hesperiaris* Kirby (Hesperiidae) are collected from leaves of their various food plants including *Agave* spp. in Mexico. Caterpillars are swallowed whole in a preserved state in a bottle of liquor ‘tequila’ (a national drink prepared from the blue agave plant), or cooked and eaten by putting one caterpillar per bottle for flavour to a ‘tortilla’ (McKenzie, 2002). Eating of the bamboo caterpillar *O. fuscidentalis* and the cassia butterfly *Catopsila pomona* F. (Pieridae), both rich in proteins (25 mg/100 g dry weight), has been reported in Southeast Asia (Yhoung-aree *et al.*, 1997). In Java, cocoons of the teak caterpillar *Hyblaea puera* Cramer (Hyblaeidae) are fried in palm or coconut oil before being consumed (Lukiwati, 2010). Local people collect sphingid caterpillars from *Colocasia* sp. (Araceae) leaves and consume them after some roasting in Papua (Ramandey and Mastrigt, 2010), or after boiling until dry in Borneo (Chung, 2010).

Odonata

Dragonflies including the larger green emperor dragonfly *Anax guttatus* Burm. (Aeshnidae) and the red-veined dropwing *Trithemis arteriosa* Burm. (Libellulidae) are collected in paddy fields in the DRC (Malaisse, 1997), the Philippines, north and northeast Thailand (Pemberton, 1995), and China (Feng *et al.*, 2001). Nymphs are often stir-fried or boiled before eating.

Orthoptera

Grasshoppers, crickets and locusts are eaten by Africans as delicacies (Mbata, 1995). Grasshoppers (Acrididae) including *Acanthacris ruficornis* Fb., *A. nigrovariegata* Bolivar, *Locusta migratoria migratorioidis* (L.), *Nomadacris septempunctata* Serville, *Cyrtacanthacris tatarica* Linn., *Lamarckiana cucullata* Stoll and other jumping insects are collected in the early morning and evening when insects gather and are inactive. Villagers use brooms made from leaves or branches of local trees to chase grasshoppers from trees and huts (Mbata, 1995; Nonaka, 1996; Roulon-Doko, 1998). In Borneo, grasshoppers are collected when cleaning the fields for paddy planting is undertaken (Chung, 2010). Small grasshoppers are first lightly salted, boiled in a little water and then simmered until dry. Sometimes they are stir-fried, while the bigger ones are deep-fried until crispy and are served without mixing with vegetables or meat (Chung, 2010). After removing the spiny legs, head, internal organs and wings, insects are cooked, fried or roasted in hot ash and sand (Nonaka, 1996). The tettigonids are fried (after removing antennae, legs and wings) and consumed by Mofu tribes in Uganda (Seignobos *et al.*, 1996). In northeast India, grasshoppers are usually collected after the harvest of paddy, especially at night. Insects are roasted or fried in vegetable oil after removing wings and the stomach and washing them with clean water. Ingredients such as ginger, garlic, chillies, salt, onions or fermented bamboo shoots are added for taste (Srivastava *et al.*, 2009). Some tribes in India eat fried grasshoppers only with salt or they put insects in a bamboo pipe for smoking for 3–4 days and eat them with chillies and salt, and/or mix them with rice (Chakravorty, 2009). In Java, grasshoppers found in rubber and teak plantations or near paddy fields are roasted after removing the wings and the legs. For taste and flavour, seasoning is done with onion, garlic, chillies and soybean sauce (Lukiwati, 2010). Japan is one of the major consumers of grasshoppers (Mitsuhashi, 1997). Whole insects are boiled before being cleaned and salted; legs are ground and eaten with groundnut butter and salt. Roasting and sautéing are common methods of cooking, after removing the wings and the legs. Seasoning with onions, garlic, cayenne and chillies peppers, or soybean sauce is done for taste. Candied grasshoppers are a favourite cocktail in Japan (Mitsuhashi, 1997). In the off-season, locusts and grasshoppers are sun-dried before storage, pounded into powder and eaten with maize flour in porridge in sub-Saharan Africa (van Huis, 2003).

Mole crickets including the common species *Gryllotalpa longipennis* (Burm.) (Gryllotalpidae) are collected mostly during summer flights or from fields of paddy, maize or sugarcane while ploughing before planting (Chakravorty, 2009; Chung, 2010). In Thailand, a small hole is made in the ground near the nest and water is poured into it. The crickets come out to the surface and are easily collected by hand (Hanboonsong, 2010). Farmers stir-fry the insects without oil (Chung, 2010).

Early morning when crickets rest on grasses or low tree branches is the ideal time for collection. In Africa, common species of field crickets (Gryllidae) include *Acheta* spp., *Brachytrupes membranaceus* (Drury) and *Gryllus bimaculatus* DeGeer, which are trapped with baits using fruits (Mbata, 1995; Seignobos *et al.*, 1996). In the case of Asian dune crickets, *Schizodactylus monstrosus* (Drury) and *S. tuberculatus* Andre (Schizodactylidae), adults are collected and put inside a bamboo pipe and smoked-dried for a week, then crushed into powder and mixed with chillies, salt and bamboo shoots. Otherwise, this powder is taken with rice or with 'apung' (a local drink; Chakravorty, 2009). In the Philippines, crickets are sautéed in garlic and onions and seasoned with soybean sauce, vinegar and hot pepper. In some areas, coconut milk is added to create a thick sauce (Adalla and Cervancia, 2010).

Current challenges and perspectives

(1) Export figures are rarely published. As such, an import of dried caterpillars from the DRC to the extent of 5 tonnes by France and 3 tonnes by Belgium (Johnson, 2010), and wasp foods by Japan from Korea, China and New Zealand (Nonaka, 2010) has been reported. Thus, business firms should exploit the export potential of insects as it is being practised for tortillas through the Torti Mundo Company and Atlanta Bread Company International, Inc. in Mexico and the USA, respectively (Munoz, 2008). The stir-fried coconut rhinoceros beetle grub (known as 'dunag' in Thai) is a delicacy in the Krabi Province, a top tourist destination in Thailand (Ratcliffe, 2006). Bugs as a snack with beer is a popular dish in Laos (Boulidam, 2010). Several recipes based on edible insects are now readily available (Gordon, 1998; Ramos-Elorduy, 1998).

To attract tourists by improving palatability of edible insects, insects can be pounded into baking powder, which may be appreciated by those who do not like to see insects (Cerda *et al.*, 2001). Similarly, flavour is one of the essential determinants by which insects are considered edible (MacEvilly, 2000). Crickets, silkworm larvae/pupae, ant pupae, giant water bug and cicadas cooked with rice and vegetables are now served in local eateries in the USA (Gracer, 2010). Also, commercial value addition is possible by way of new preparations, such as lollipops with ants, insects as a condiment in modern recipes, feed for chicken and dead insects as decorative items (Fairman, 2010). To incorporate entomophagy in Western diets, insect clubs are being established in the USA where insects can be sold as food packets along with other food items. This venture may be interesting for poor countries as a new source of family income.

Along with insects, eating of spiders is a traditional practice in several ethnic groups in northeast India, Papua New Guinea, Australia, New Zealand (Meyer-Rochow, 2005) and central African countries (van Huis, 2003). These local products, by-products and recipes can be promoted, as opportunities exist for improved packaging and marketing (Ramos-Elorduy, 1998). Also, the intellectual property issues are to be applied to insect recipes (Sirimungkarakat *et al.*, 2010).

(2) Locals know which insects are edible as well as where and when to find them, and how to catch them. Therefore, indigenous people practising entomophagy should be involved in future projects. In fact, farming communities are willing to rear

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insects for sale with a hope of removing the negative stigma associated with eating insects and show urban consumers how healthy the habit of eating insects is. For this venture, large-scale production and marketing networks are essential. The basic idea is to design factories in future where insects would be mass-reared, harvested and processed in an industrial way. This may result in cheap and controlled food production and poor people can afford it at least in a period of general food shortage.

(3) Knowledge of the potential of edible insects is to be disseminated for new consumers, especially in urban areas. This gap in information can be filled by documentation of rural livelihoods depending on entomophagy and traditional knowledge. Also, ecological knowledge can provide an opportunity for insect conservation and ultimately food security (DeFoliart, 2005). Creating awareness in the Western world that insects are a traditionally and nutritionally important food for many tribes may increase pride in ethnic roots and traditions, and raise concern about a healthy environment and overuse of pesticides; and may foster communication among scientists who are interested in the subject.

(4) What is needed is to link forest management with insect conservation to facilitate sustainable harvesting of wild insect populations because entomophagy can make a significant contribution to insect conservation if insects are substantially harvested in conjunction with habitat management, including biodiversity preservation, which is an important factor for maintaining insect populations (DeFoliart, 2005). This strategy can be implemented by integrating traditional and ecological knowledge that results in economical values (Losey and Vaughan, 2006; Charnley *et al.*, 2007). Management practices for major host plants of edible insects should be developed to continuously supply food to them. Wood exploitation from forest areas results in reduction in the forest cover (Reid *et al.*, 2004) wherein most of the edible insects live and their population density is maintained. An ideal forest management involving the adoption of rotational burning, promotion of green vegetation, controlled mosaic burning and reduction of insect harvestings can enhance insect survival and augmentation. This policy needs efforts of government departments by way of subsidy or financial incentive for conservation of natural resources because despite community efforts, there has been degradation in insect resources due to reduction of areas under forests that are being used by tribal communities for fuel wood.

Insect populations are often diminished due to commercial exploitation, bush fire, unfavourable climatic factors and attack of natural enemies (Yen, 2009b). In Mexico, 14 insect species are considered as threatened because they are overexploited for food in restaurants and for export purpose rather than as a source of food for locals (Ramos-Elorduy, 2006). On the contrary, whenever there is explosion in insect populations, the pests attack and damage food crops. This situation may create conflicts between farmers and foresters who eradicate insects and local people who rely on the availability of insects for food. Measures to preserve the edible insects, particularly those which are threatened, are needed. For this purpose, research on biodiversity of insects in forest ecosystems on the basis of traditional regulation should be intensified and promoted, for instance along the principles practised by the Bisa community in northern Zambia (Mbata *et al.*, 2002). Collecting insects by people migrating from neighbouring regions has been reported from Mexico by Ramos-Elorduy (2008). This practice may no longer be allowed by adopting a legal code.

Overexploitation has degraded the ecosystems, resulting in unstable abundance of insects (Ferreira, 1995). For the effective management of insects and forests, Mbata *et al.* (2002) suggested a workplan for the preservation of commercial caterpillars in Zambia, namely studying the ecology and monitoring the population dynamics of these insects on at least 20 tree species, protecting their host plants against late bush fires, and restricting insect harvesting. Thus, the mopane caterpillars are now studied to see whether more sustainable harvest will result in enhanced economic stability and conservation becomes stable (Frears, 1995).

(5) Forests are preferred for insect harvesting because there is no insecticide use. Their collection in established crops or horticultural systems is also practical (Banjo *et al.*, 2006*a*) since insects can be mass-collected by hand and through use of light or pheromone traps. By this way, insect populations are reduced in the crop, and often, curative measures are no longer needed (Hunter, 2004; DeFoliart, 2005). For example, the egg density of a grasshopper *Sphenarium purpurescens* Charpentier (Acrididae) in Mexico was lesser in fields where mechanical picking of insects was practised than in those fields with insecticide applications, and hand collection of the Bombay locust *Patanga succinta* L. (Acrididae) from maize fields reduced pest infestation levels in Thailand (Boongrid, 2010). In such cases, expenses on plant protection are reduced because less quantity of pesticides is needed, and the risk of soil and water contamination is minimized (Cerritosa and Cano-Santana, 2008). Therefore, entomophagy may be integrated effectively and practically in existing integrated pest management strategies. This possibility, however, needs to be thoroughly studied before any recommendation is made to farmers because

hand-picking becomes expensive whenever labour is expensive or not available.

(6) Silkworm pupae contain proteins, peptides and amino acids and are generally considered safe for human consumption (Zhou and Han, 2006). However, some insects may be toxic to humans. Traditional methods are, therefore, used to remove the poison before eating (van Huis, 2003). Allergic reactions after consuming silkworm pupae (Liu *et al.*, 2001) or grasshoppers (Vetter, 1995; Srivastava *et al.*, 2009), or cocoons of the teak caterpillar *H. puera* (Lukiwati, 2010) have been reported. Eating poisonous beetles and caterpillars can result in lead poisoning (Phillips and Burkholder, 1995). Similarly, undifferentiated schizophrenia had been observed in local populations in south India (Lingeswaran *et al.*, 2009). Poisoning may occur due to misidentification of edible species. For example, eating of a blister beetle (*Mylabris phalerata* Pallas (Coleoptera: Meloidae)), which contains the toxin canthardin, resulted in human death in Thailand (Hanboonsong, 2010). It is speculated that excessive consumption of insects with chitin, protein or fat carries a risk of urinary tract stone formation and development of chronic degenerative disease (Yhoung-aree, 2010). As a preventive measure, MacEvilly (2000) suggested that insects should not be eaten with nuts or shellfish as both have been shown to trigger allergic responses in hypersensitive individuals. These assumptions need further studies to verify and conclude ill effects of entomophagy.

(7) Pesticides (insecticides, acaricides, rodenticides, fungicides, herbicides and molluscicides) used in controlling various pests, weeds and plant diseases of food crops or forest trees can make insects unsuitable for human consumption because their residues are accumulated in the tissue (Capinera, 2004; Chakravorty, 2009). Yet, consumers often eat pesticide-contaminated insects without prior knowledge (unintentional entomophagy). In future, it would be better if insects are consumed with no or low pesticide residues, but the challenge will be how and where to procure pesticide-free insects.

(8) In the USA and Europe, entomophagy is uncommon and even a taboo in many cultures (Yen, 2009*a*; Meyer-Rochow, 2009). This cultural bias against eating insects is still unclear (DeFoliart, 1999; Ratcliffe, 2006). On the contrary, in certain African countries such as Botswana, South Africa and Zimbabwe, both animal husbandry and eating of mopane worms and other insects have co-existed for centuries. This perspective has to be studied for long-term economical and ecological benefits, and perpetuated by local traditions.

(9) It is impossible to completely eliminate insects from the human food chain, as they are carried in storage places or market yards along with the harvested crop produce (food grains, vegetables and fruits). Sometimes immature stages (live or dead) or insect fragments are present since they could not be killed or removed in the field or in the storage structures. In many instances, insects have been ground up into tiny pieces in food items. Of course, these insects may make food products nutritious and provide some minerals and vitamins, but, again, eating them may pose health hazards. Therefore, precautions are to be followed before eating.

(10) The small size of insects makes the collection, rearing and processing (including removal of all organs containing waste products that may be poisonous) rather difficult. In the case of large insects, proper disposal of intestinal contents and maintenance of good sanitary conditions in production should be followed (Allotey and Mpuchane, 2003) because during harvesting, handling, processing/drying and storage, insects can come in contact with soil and can be contaminated with pathogenic micro-organisms causing spoilage (Banjo *et al.*, 2006*b*). Some insects serve as vectors or intermediate hosts for vertebrate pathogens such as bacteria, protozoa, viruses and helminths, thereby increasing the risk of disease transmission to humans. Naturalists and amateurs claim that insects consume clean fresh green leaves and so contamination is prevented. In reality, edible insects can be contaminated with bacteria, fungi and pesticide residues. Therefore, food safety guidelines should be available to assist both vendors and consumers. The food regulatory laws against insect contamination in many countries are in practice, and foods derived from insects are inspected or tested and approved as safe food (Mulhane *et al.*, 2001; Ministry of Health, 2003; Zhou, 2004). In the case of defaulters, the Food and Drug Administrations take appropriate legal action on this matter (Zhou, 2004; Srivastava *et al.*, 2009).

(11) When control measures are applied against insects, some populations survive. The survivors increase due to adaptation to the local environment and their population, though at a low level, is maintained in the ecosystem. The availability of insects is thus assured to locals. Traditional dishes that are under threat as new generations imitate the Western taste for meat may be brought back in the mainstream of entomophagy by way of promotion by organizing shows, interactive displays, street plays and exhibitions (Fairman, 2010). To exploit marketing, existing technologies for the processing of edible insects are to be improved and disseminated to tribal communities. Insect species with high nutritional content ought to be reared with modern techniques to increase their commercial value and availability to consumers. Awareness

needs to be encouraged with thrusts on environmental benefits, nutritional value, availability of insects in the period of food shortage and for ritual ceremonies, and so on. This would possibly give access to improvement in insect rearing, quality control and to the avoidance of pesticide contamination. Further, these initiatives would create marketing avenues particularly in cities and towns where product quality, labelling and attractive packaging are necessary for value addition.

Conservation and collection of insects in nature

Van Huis (2003) discussed various methods of collection and capture of edible insects. Harvesting of insects is often done by women and in some regions, by children, for whom insect farming can be a low-input sustainable form of agriculture. The way of collecting depends on the insects' behaviour. For example, low temperatures in the morning make insects comparatively inactive and catching them is easy; nocturnal insects (termites and grasshoppers) can be caught in light traps as they are attracted to light; artificial breeding sites are useful for attracting palm weevils, whereas crickets and cicadas can be traced by the sound they make (van Huis, 2003).

Getting a large number of insects in the wild is often uncertain due to their unpredictable locations and population density. Research on management potential of wild edible insects will enhance harvests, ensure sustainability in nature and create potential and economic feasibility of mass collection of promising species by local people who can eventually contribute to rural food stocks and earn their livelihood as demonstrated by Munyuli Bin Mushambanyi (2000) for the brown silkworm *Anaphe infracta* Walsingham (Lepidoptera: Notodontidae) in the DRC. Shifting crop cultivation is another way to improve caterpillar production in northern Zambia (Chidumayo and Mbata, 2002).

Insect mass rearing in captivity at village level

Development of economically feasible ways of mass rearing in closed environments is crucial since most insects are only seasonally available in nature (Callavo *et al.*, 2005; Feng *et al.*, 2009; Sileshi and Kenis, 2010). Rearing of insects in captivity (cages, potted plants and rooted food plants) at village level can allow a continuous supply rather than relying on natural harvesting. For example, the hepialid caterpillar *Wiseana copularis* Meyrick (Lepidoptera: Hepialidae) (Allan *et al.*, 2002) and the South American palm weevil *Rhynchophorus palmarum* L. (Cerda *et al.*, 2001) can be reared on alternative host plants or artificial diets (semi-synthetic/synthetic). Indoor rearing by farmers of the eri silkworm and mulberry silkworm in houses in India (Sathe *et al.*, 2008; Chakravorty *et al.*, 2011; Sarmah, 2011), the giant hornets (*Vespula* spp.) in wooden hive boxes in Japan (Nonaka, 2010) and the eri silkworm on cassava leaves in Thailand (Sirimungkarakat *et al.*, 2010) has been quite successful and has become a routine commercial activity. In Thailand, farmers use cement tanks or wooden containers covered with a plastic sheet for cricket farming (Hanboonsong, 2010). A layer of sandy loam soil is added and is covered with dry grasses, bamboo shoots or egg cartons to provide shade for the crickets. Egg masses are introduced and containers are covered with nylon nets. An artificial diet, containing chickfeed along with grasses or weeds, and water are provided. After 4–6 weeks, adult crickets are ready to be harvested (Jamjanya *et al.*, 2001).

It is possible that the sale of insects yields more revenue for farmers than millet in the Sahel (van Huis, 2003), where small-scale production units with simple techniques of mass rearing can be started. If insects are reared or collected in surplus, preservation by drying can promote cottage industries through remunerative business. Thus, controlled rearing should move from small units to an industrial phase with adoption of economical mass production on a large scale (Hardouin, 1995). Of course, commercialization is hampered by taxonomic uncertainty and lack of information on the biology of certain insects (Yen, 2010). New research should therefore tackle insect identification, ecology and nutritive value of insect species that have short life cycles, and are thus most suitable for mass rearing. Recently, low cost techniques for mass rearing of edible insects, including crickets, grasshoppers, ants and the giant water bug, have been successfully developed in China, Korea and Thailand (Kim *et al.*, 2008; Feng *et al.*, 2009; Boulidam, 2010).

Documentation on edible insects is scattered and not easily available. Compilation of recent research findings on consumption, traditional harvesting and management practices is essential. Promotional and educational aspects through extension services should include assurance of quality and safety of insect products. The World Conservation Monitoring Centre in the UK maintains conservation status of insect species under threat/extinction. Similar efforts are needed for edible insects. Developing protocols for recording data on edible insects and establishing a centralized database or a collaborative network can facilitate sharing of information and exchange of insects and insect products. At government level, efforts are needed to include edible insects in the government policies on food security, and rural development strategies should be based on their diversification in agriculture and forestry. Establishment of a global bank of edible insects may open new avenues in research and development, ultimately proving advantageous for food security projects.

Chitin/chitosan comprises 10% of whole dried insects, which can be extracted from the host cuticle in a much easier way than that of crustaceous chitin (Duan, 1998). Experiments on the silkworm pupa have demonstrated the significant value of chitin as a source of fibre and calcium (Zhang *et al.*, 2000; Paulino *et al.*, 2006). Thus, protein concentrates from de-chitinized insects can be produced on a large scale and fed to animals.

Insects are considered as an alternative source of diet not only for space agriculture for eventual habitation on Mars (Katayama *et al.*, 2005) but also for any close space environment (Mitsuhashi, 2007). The aeronautical prospects being bright, insects should be considered as a nutritious food for astronauts and as a key to space agriculture (Katayama *et al.*, 2008). For this purpose, rearing techniques for silkworms, termites and flies have been developed and continuous cell-culture systems have been recently created (Mitsuhashi, 2010).

Among insects used in entomophagy, mealworms, the house cricket, acridids and the silkworm *C. forda* (Westwood) (Lepidoptera: Saturniidae) can be raised as a valuable and cheap protein feed for fish and poultry (Ramos-Elorduy *et al.*, 2002; Oyegoke *et al.*, 2006; Anand *et al.*, 2008). Farmers also will earn extra income from this enterprise.

Conclusion

Awareness of entomophagy among consumers and insect-rearing entrepreneurs is necessary (Nonaka, 2005). In some instances, consumers are willing to pay a premium for the safety of street foods including insect preparations if prepared, stored and sold in a hygienic condition (Akinbode *et al.*, 2011). Such an attempt was made in 2010 in the USA by organizing an international seminar on ‘The potential of edible insects’ at Linvile, Alabama, USA, by the Southern Institute for Appropriate Technology. Similarly, a workshop at Chiang-Mai in Thailand on ‘Edible insects’ co-organized by the FAO in 2008 was a great success. After all, entomophagy can be revalidated by worldwide campaigns that are to be launched in those countries that are facing acute food shortage. Joint concerted efforts to popularize entomophagy through collaboration among developed and developing nations should be initiated. Extensive surveys of insects, search of literature, research on nutritional value of unknown species as well as socio-economic aspects (including acceptance of these foods by consumers) would open new vistas for food security. A multi-faceted and linked global strategy is, therefore, needed to ensure sustainable and equitable food security (FAO, 2010*a*), and entomophagy can play an inter-disciplinary role associated with forestry, traditional medicine, agriculture and animal husbandry.

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