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Effects of formulation and process conditions on microstructure, texture and digestibility of extruded insect-riched snacks

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ABSTRACT

Extruded cereals made of wheat flour and grinded Yellow mealworm larvae (*Tenebrio molitor*) were produced to investigate the effect of insect inclusion (0%, 10%, 20%) and processing conditions (barrel temperature and screw speed) on their nutritional content, microstructure, texture and digestibility. Snacks enriched with 10% mealworm powder shifted their macronutrient composition towards a protein content high enough to claim the food as "source of protein" according to European food regulation. At 10% of enrichment, the adoption of high barrel temperature and screw speed significantly improved the microstructure, in terms of expansion and pore structure, delivering acceptable textural qualities. At 20% substitution, snacks showed poor expansion properties, mainly due to the presence of fat in the larvae. Starch and protein digestibility of were correlated with microstructure properties as a function of porosity, pore size and wall thickness. Interestingly, mechanical forces generated in extrusion likely improved the digestibility of *T. molitor* proteins which are tightly bound and sclerotized to the exoskeleton. Tailoring processing conditions and formulation insect ingredients can be successfully incorporated into extruded cereal snacks.

Industrial relevance: This study evaluated the nutritional and technological properties of extruded cereal snacks enriched with an edible insect powder (*T. molitor*). Results suggested that edible insects can be used as novel ingredient in extruded snacks and pointed out how processing conditions can modulate snack digestibility.

1. Introduction

Insects are highly valued as tasty and nutritious food by over 2 billion people mostly living in Asia, Africa and South America (FAO, 2013). Given the wide range of edible insect species, over 2000 reported by Jongema (2013), their nutritional composition vary largely, displaying a broad range of protein, fat and carbohydrate concentrations (Raubenheimer, Rothman, Pontzer, & Simpson, 2014). Consequently, some species containing high amounts of specific nutrients represent a promising, yet underexploited food source. For instance, species of the order Orthoptera (grasshoppers, locusts, crickets) can contain up to 77% protein (dry basis) while a fat content of about 77% fat is reported for larvae of *Phassus triangularis*, Lepidopteran (moths and butterflies) (Ramos-Elorduy, Pino-M, & Cuevas-Correa, 1998). Furthermore, insects are also rich in important minerals, including copper, selenium, iron, zinc, magnesium, manganese, phosphorous, and vitamins like biotin, riboflavin, pantothenic acid, and folic acid (Rumpold & Schlüter, 2013).

Recently, insects have gained much interest in Western societies, especially as an alternative source of protein. One of the main advantages over other protein sources is the low environmental costs of production, which becomes essential to satisfy the rise in the global proteins demand (van Huis, 2013). Nevertheless, for distribution of edible insects on industrial scale different challenges need to be addressed, covering the development of automated rearing facilities, safe hygienic processing practices, and the establishment of international food regulations (Rumpold & Schlüter, 2013).

Westerners show a great aversion towards the consumption of insects. To date, rejection towards insects has been mainly attributed to cultural and psychological barriers (Harris, 1985) and association with unhygienic or rotten foods (Caparros Megido et al., 2016). However, several studies show that presenting insects invisibly within familiar preparations may be effective to reduce negative perceptions and to increase their acceptance (Hartmann & Siegrist, 2016; Looy, Dunkel, & Wood, 2014; Tan et al., 2015; Tan, van den Berg, & Stieger, 2016). Recently, Le Goff and Delarue (2015) reported that consumers reject the idea of tasting chips made by an invisible insect based flour, but they accept it after the first bite, suggesting that processing insects to

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create appealing products may be a good strategy to vehicle insect into food designed for Western consumers.

Ready-to-eat expanded snacks are very popular among Western consumers principally due to their convenience, attractive appearance and unique texture attributes. In fact, the consumption of expanded products has increased tremendously in recent years and their global market is projected to reach 31 billion dollars by 2019 (marketsandmarkets, 2014). Expanded snacks are produced through the extrusion-cooking technology, which is an efficient manufacturing process. By combination of mechanical shear, high temperature and high pressure, starch solid materials are converted into a viscoelastic fluid that is pushed by a screw through a die. The sudden decrease in pressure vaporizes the water embedded in the fluid, leading to the formation of a solid foam with specific structural characteristics (pore wall size and thickness, porosity, density) and mechanical properties (Guy, 2001). Although starchy materials are the most suitable to deliver good technological features for production of acceptable snacks, they are often low in protein and dietary fiber being unable to satisfy the needs of an increasing number of health-conscious consumers (Brennan, Derbyshire, Tiwari, & Brennan, 2013).

Improving the nutritional value of these types of snacks is a twofold opportunity either for consumers' health and food industries. Up to now the focus of the nutritional improvement was on whole grains, addition of legumes and other functional ingredients, which cause a decrease of sectional expansion and density, thereby increasing hardness of extruded products (Chanvrier, Desbois, et al., 2013; Lazou, Michailidis, Thymi, Krokida, & Bisharat, 2007; Ramos Diaz et al., 2015; Robin et al., 2012; Sumargo, Gulati, Weier, Clarke, & Rose, 2016; Yu, Ramaswamy, & Boye, 2013). To date, the use of edible insects in expanded extruded snacks has not yet been investigated. Besides the foreseen progress of insects' fractionation systems to obtain protein, fat and chitin, the incorporation of insects invisibly into familiar foods like snacks may be a valid strategy to speed their adoption among consumers.

This paper investigates the effects of Yellow mealworm larvae added to extruded snacks. The enrichment in insect powder has been studied at different operating conditions with two main aims: (i) to assess the microstructure and texture properties of the extrudates; (ii) to evaluate the digestibility of the obtained final products.

2. Materials and methods

2.1. Materials

Wheat flour of type 0 was supplied by Molino Taramazzo (Pezzolo Valle Uzzone, Cuneo, Italy). Larvae of Yellow mealworms were supplied in dry form by from HaoCheng Mealworm Inc. (Xiangtan, Hunan, China). Larvae were microwave dried by the provider maintaining the temperature below 80 °C. Dry larvae were ground for 60 s at 6000 rpm in a knife mill (Grindomix GM 200, Retsch, Germany) to pass through 900 µm sieves. Three blends of wheat flour and mealworm powder were formulated in mass ratios of 100:0, 90:10 and 80:20 on a dry matter basis (Table 1). Before use, the blends were mixed through a planetary mixer (cooking chef, Kenwood Ltd. UK).

2.2. Extrusion processing

The extrusion trials were conducted using a co-rotating twin-screw extruder (BC-21 extruder, Clextral, Firminy, France). The barrel consisted of nine independent zones with a total barrel length of 900 mm. The screw had a distance between shafts of 21 mm (L/D = 36:1), and a circular die opening of 5 mm. Further specifications on the screw configuration are described by De Pilli, Carbone, Derossi, Fiore, and Severini (2008). The extruder was operated at a constant feed rate of 10 kg/h and 18% moisture dry bases. The decision of the hydration regime was based on preliminary trials. More specifically, higher moisture values (20%) led to very poor expansion at all processing conditions, and the use of lower moisture (16%) caused clogging of the feed material in the barrel.

Table 1
Formulation and extrusion conditions used for the processing of Exp.1 and Exp.2 and moisture loss of extrudates at the die. Temperature of the last three zones are reported.

Samples	Wheat: mealworm ratio	Barrel temperature (°C)	Screw speed (rpm)	SME (kJ/kg)	Moisture loss (%)
Experiment 1					
i0	100:0	120, 150, 160	400	485	40.3 ± 0.3
i10	90:10	120, 150, 160	400	339	32.3 ± 0.3
i20	80:20	120, 150, 160	400	166	9.9 ± 0.4
Experiment 2					
i1	10	100, 110, 120	240	155	17.8 ± 0.3
i2	10	100, 110, 120	320	244	27.0 ± 0.2
i3	10	100, 110, 120	400	445	26.9 ± 0.2
i4	10	110, 130, 140	240	127	18.7 ± 0.1
i5	10	110, 130, 140	320	197	27.4 ± 0.2
i6	10	110, 130, 140	400	392	28.8 ± 0.1
i7	10	120, 150, 160	240	104	32.4 ± 0.1
i8	10	120, 150, 160	320	170	35.6 ± 0.1
i10	10	120, 150, 160	400	339	32.3 ± 0.3

SME: specific mechanical energy.

Blends were extruded in two sets of experiments as reported in Table 1 and herein referred to as Exp.1 and Exp.2. In the first experiment three different formulations containing a mass fraction of 0, 10 and 20% of grinded mealworms were extruded as reported above, while in the second experiment the formulation containing 10% grinded mealworms was processed with 9 different combination of extruder screw speed and barrel temperature. The rationale for choosing the formulation of 10% was to fully study the effect of temperature and screw speed, and build a complete design of experiments with these factors while still maintaining an average level of insect enrichment.

In all experiments, temperature profile of the first six zones was set at 30, 30, 50, 60, 80 and 100 °C in forward order, while temperature of the last three zones and screw speed were set as reported in Table 1. Specific mechanical energy (SME) was computed according to De Pilli et al. (2008). After extrusion, samples were dried at 50 °C for 6 h, sealed in plastic bags and stored at − 20 °C till the experiments.

2.3. Nutritional analysis of extruded products

Extruded snacks were milled to pass through 90 µm sieves and analysed for total starch by Megazyme total starch kit K-TSTA 09/14 (AOAC, 2005); lipid by Soxhlet extraction (AOAC, 1920); ash by gravimetric method (AOAC, 1923); protein content, analysed by Dumas method of combustion (AOAC, 1996) using a Nitrogen/Protein analyser (model FP-528, Leco St. Joseph, USA). EDTA was used as standard (Elemental Microanalysis Ltd., Okehampton, UK). Different nitrogen-protein conversion factors were used for each formulation. Proteins in wheat flour and mealworm powder were calculated by using respectively 5.71 and 6.25 N conversion factor. For blends, the N-conversion factors were computed as weight average between single N-factors and protein content.

2.4. Expansion characterization

2.4.1. Moisture analysis

Moisture loss corresponds to the moisture content of extruded snacks at the die exit and it was computed by subtracting the residual moisture from the in-barrel moisture. Moisture was measured according to AOAC (1999) on six replicates.

2.4.2. Microstructure

Microstructural features of the extruded products were analysed