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Evaluation of crises suitability of food systems: a comparison of alternative protein sources

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Abstract
Global crises affecting food security have kept increasing for four years in a row, with almost 350 million people expected to suffer from food insecurity in 2023, more than double the number compared to 2020. This draws attention to the importance of finding food capable to feed a population under such conditions. In this research criteria were developed to gain comparative insights into crises suitability of food system's food security. Four principal criteria – production characteristics, intrinsic attributes, supply chain efficiency, and feasibility of conversion – were identified to encompass this crises suitability, and translated into measurable indicators tailored to protein foods. A multi criteria analysis (MCA) was developed which enabled the assessment of different alternative protein sources – insects, cultured meat, mycoproteins, algae, and plant proteins – on the basis of equal importance of the crises suitability criteria. Chicken meat, being currently the most efficient protein source in times of crisis, was used as a reference protein source. Based on the suitability criteria, insects and cultured meat resulted from the comparative study convincingly as the most suitable to replace chicken meat. Although the systems of the other alternative protein sources did not emerge as suitable options to replace chicken meat in a crisis, algae, mycoproteins, and plant proteins could support chicken meat as complementary sources of proteins if embedded in the food supply. When adopting these criteria, the type of crisis needs to be taken into account to judge the relative importance of the criteria, as a basis for decision making on the crisis suitability of food stuff's systems. The methodology applied allowed to identify a clear distinction between crises suitability of alternative proteins systems, and has therefore potential for application to other food systems. Then, the indicators for the criteria need to be tailored towards the nature of the specific food system.

Keywords Food crisis · Crises suitability · Food security · Alternative protein sources · Food system · Multi criteria analyses

1 Introduction

In the past four years, the frequency and intensity of crises affecting food security has kept increasing, among others caused by climate change, pandemics, and conflicts (FSIN, 2022). Food security is defined as "for all people at all times to have access to sufficient, safe and nutritious food to maintain a healthy and active life" (FAO, 2006). In September 2022, more than 205.1 million people reached the three highest phases of acute food insecurity. This number is estimated to almost double by the end of 2023, with almost 350 million people globally in conditions of food insecurity (WFP, 2023). To prevent negative food security effects triggered by similar events in the future, FAO, IFAD, UNICEF, WFP and WHO (2020) emphasized the importance of achieving more efficient and sustainable food productions as key to ensure food security even when crises occur. Urgent changes are needed to allow food systems to be food secure under crisis conditions (Stringer et al., 2020). An assessment of food systems on their food security under crisis conditions is needed to envision these changes. However, evaluation of food systems against the background of crises are fragmented as they seem to address different aspects of food systems such as logistics (Alexander et al., 2017; Melgar-Lalanne et al., 2019), production (Bleakley & Hayes, 2017; Wiebe, 2002) or focused on specific topics such as health (Becker, 2007; Boland et al., 2013). As the definition of food

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security entails several aspects, including access, quantity, safety, nutrition, according to the definition of FAO (2006), it is important to take the integral food system within the context of crisis as starting point for analyzing food security. Such an integral approach is lacking in literature as far as we know.

The value of a food system approach to food security is to have a holistic overview from 'field to fork' activities, but also includes socio-political and environmental circumstances which as well influence the food security outcome (Ericksen et al., 2010). The (global) food system is a complex and 'vast machine' which consists of a food production system and a food consumption system, encompassing food access and utilization (Savary et al., 2020). To be able to concretely analyze this complex and encompassing system, a connecting principle which defines the food system against the background of food security is needed. This connecting principle is an individual food stuff. The argument for this choice is that a food system seizes on an individual food stuff. In this, we follow Savary et al. (2020) who explain that 'staple' food (mostly grain) and 'nutritious' food (including *e.g.,* meat, fish, dairy, fruits, vegetables), which are both essential for human health, imply different supply chains concerning production and accessibility of the particular food stuffs. Evaluating food secureness of food systems in crisis conditions hence implies that particular foods with their food systems' implications can be used as a starting point for evaluating food system's security under crisis conditions. Thus, concept of "food system" encompasses production, processing and distribution activities up to the consumer for a particular food within a certain context.

Evaluating food security under crisis conditions greatly differs from that in a 'normal' situation (Engelseth, 2016; Grófová & Srnec, 2012; Stringer et al., 2020). As the definition of food security (FAO, 2006) emphasizes the continuity of supply of nutritious and safe food to people regardless of the circumstances, the evaluation should start from the extend at which a crisis disrupts consumers' access to foods. When the supply of food is impeded immediately by a strong disruption from natural (*e.g.,* earthquake, extreme weather conditions) or human generated hazards (*e.g.,* political unrest) (Hecht et al., 2019), food shortages appear (Savary et al., 2020). In such a case, a particular food system lacks robustness to deal with such an immediately effective crisis. On the other hand, trends like climate change can also threaten food security *e.g.,* because of changing production circumstances. However, this type of evolving crisis gives room to adapt food system characteristics to new circumstances (Hecht et al., 2019). Hence, the relation between crisis and food security can be characterized by time constraints in terms of immediate or a near or distant future threat of disruption of foods materials' food security for consumers. Evaluating food security considering types of crises with different time constraints, alters the crises suitability of a certain food system's food security.

As a leading concept, "crises suitability of food system's food security" is presented as a concept defined as the suitability of a food system to offer to consumers nutritional value in a crisis situation. This concept encompasses different criteria which together should give an overview of how food is suitable to feed a population in a crisis. Multiple criteria need to be developed to cover food security of a food system under crisis conditions. This multi-criteria approach is based on a multidisciplinary effort (Gesan-Guiziou, 2020). One method for obtaining the overview of what the concept crises suitability of food system's food security entails, is the Multicriteria Analysis (MCA). This method enables a systematic and transparent approach which increases measurability and generates reproducible results by in this case comparing different food systems, relative to each other and to specific criteria (Blanco-Gutiérrez et al., 2020). This method has already been applied to aspects concerning food system in relation to food security *e.g.,* on food production and consumption and on health and nutrition (see overview Blanco-Gutiërrez et al., 2020), but never on suitability of food system's food security under crisis conditions as far as we know.

The concept of crises suitability of food stuff systems opens the necessity for practice-oriented research which ultimately could aim at supporting policy makers by choosing foods from a system's perspective for crisis situations. This implies a switch from fundamental food related research to parallel research to stimulate information flows underpinning decision making about how to get ready for crises from the perspective of food security (Amjath-Babu et al., 2020; Campbell, 2016). Although there is a vast body of literature on food security, we have not identified research on the evaluation of food security in crisis conditions from a food system approach. The current, explorative study includes a comparison within the category of protein rich foods. Proteins are one of the essential components in the fight against food insecurity. Animal proteins are by far the food products with the highest environmental impact in the current food production (Dagevos & Voordouw, 2013; Salami et al., 2019), and this impact will increase due to the expected future increased protein demand of the growing world population. Already, this longer-term crisis expectation urges to identify alternative protein sources with similar nutritional properties and lower environmental impacts that allow food security and more sustainable food production. Various studies (Alexander et al., 2017; De Boer & Aiking, 2011; Van Huis et al., 2013) already demonstrated that alternative protein sources – *e.g.,* insects, cultured meat, mycoproteins, algae, and plant-proteins – are promising in the realms of nutritional value and sustainability.

The overall aim of this study is to develop, apply and evaluate possibly divergent criteria that cover crisis suitability of food's system. As this is the first and explorative study into crises suitability of food systems' food security, this study will cover the first three steps of an MCA analysis which are (1) assessing the goal/definition of the problem, (2) determining criteria and indicators and (3) standardizing the criteria (see Section 3), with application to alternative protein sources.

Therefore, this article is divided in two main parts (1) to develop the concept of crises suitability of food system's food security and present relevant measurable indicators for this concept and (2) to apply this set of indicators in a comparative study of alternative protein sources.

2 Methods

To be able to perform an MCA on 'crises suitability of alternative proteins system' food security' literature searches were administered to develop the concept of the 'crises suitability' of a food's system. From the literature search, the values for the crises suitability indicators of both chicken - and alternative proteins systems were retrieved. Moreover, a method was developed to perform a comparative analysis between the alternative protein sources and the reference food stuff system.

2.1 Developing the concept of crises suitability of food system's food security into criteria and indicators

Around a dozen scientific publications related to different types of crises where food security was at risk (*e.g.,* wars, famines, space travel, etc.) were analyzed. Publications were first selected based on their title and abstract, then entirely read when deemed pertinent for the scope of the research. The information related to the three main pillars of food security – availability, access, utilization – was extracted to identify the main indicators influencing 'crises suitability' of a food's system to improve food security under crisis conditions. A second semi-structured literature study of publications on food crises was performed to identify measurable indicators for each criterion. In view of the application with respect to alternative protein sources, part of the indicators, especially those with respect to nutritional value, were worked out in a protein specific manner. A tree diagram of the criteria and their indicators was built to enable a visual representation of the supply chain capability framework.

Key search terms used for this step were: "food supply chain capability crisis", "food requirements security crisis", "food production crisis", "food intrinsic attributes crisis", "food supply chain risk management crisis", "space food nutrition" and "pandemic food security".

2.2 Assessing the values of the reference – chicken meat

A reference was set to compare alternative protein sources to an already present efficient protein source, in this case chicken meat. Chicken meat was selected as it was demonstrated to be the most efficient conventional protein (Terluin et al., 2013). However, this choice was based on Western European conditions in which *e.g.,* geographical circumstances play a role in the production of this protein source. The same research could be performed with other protein sources that are more relevant in another geographical location where a food system like the chicken-system is possibly less applicable. 'Chicken' as a reference could then be replaced, *e.g.,* by fish in coastal areas or sheep or goat in mountainous regions.

The crises suitability criteria 'Availability-production characteristics', 'Utilization-intrinsic attributes', 'Access-supply chain efficiency' and 'Access-feasibility conversion to crises', were applied to chicken meat and data were gathered from literature for the underlying indicators. At least two publications were used for each indicator to improve the reliability of the research. Around 25 scientific publications were analyzed to assess the value of each indicator. The values of chicken meat were then used as references for comparison. Key search terms for this step were: "chicken production characteristics", "chicken intrinsic attributes", "chicken supply chain", "chicken production", "chicken meat safety", chicken meat nutritional values" and "chicken production technology".

2.3 Assessing the values of the alternative protein sources

The values for the indicators of the criteria of the selected alternative protein sources – insects, cultured meat, algae, mycoproteins and pulses – were extracted. Despite the vast number of insect species consumed worldwide, the research focused exclusively on mealworms (*Tenebrio molitor*), to allow a clearer and more precise overview of insects as an alternative protein, as the first insect species which consumption was authorized in Europe (EC, 2023). When possible, at least two publications were used for each indicator to improve the reliability of the research. Safety and amino acid indicator were the only values for which only few publications could be found. Around 60 scientific publications were analyzed for this step, equally divided between the alternative protein sources. Key search terms were for each alternative protein source:

"production characteristics", "production requirements", "intrinsic attributes", "nutritional values", "supply chain", and "technology requirements production".

2.4 Comparing the alternative protein sources to chicken meat

A method was developed to compare the values of the indicators of each alternative protein source to the reference values of chicken meat. The comparison of these to the criteria-values of chicken meat, resulted in the ratings "more suitable than chicken", "as suitable as chicken", or "less suitable than chicken". Alternative protein sources rated as suitable, or more suitable than chicken, were considered as a viable option to embed in the food supply if a crisis had to occur. To allow a better overview of the crises suitability of each alternative protein system, a color scheme adapted to the different ratings of suitability was applied into a tree diagram; green for the indicators assessed as "more suitable than chicken", yellow for the indicators assessed "as suitable as chicken", and red for the indicators assessed "less suitable than chicken".

When judging the overall crises suitability of alternative proteins systems' food security, we should take into account that the crisis suitability indicators can be conflicting amongst themselves. Taking one indicator *e.g.,* nutritional value measured by protein content, one could state that these are one of the essential components in the fight against food insecurity. However, taking multiple aspects into consideration, we see that for instance animal products which are high in proteins, are by far the food products with the highest environmental impact in the current food production (Dagevos & Voordouw, 2013; Salami et al., 2019). This environmental impact will increase due to the expected future increased protein demand of the growing world population. Hence, a multiple criteria perspective on animal proteins learns that a high nutritional value is combined with, at the least, less sustainable production conditions. These are then judged to be conflicting indicators considering the severe implications for food security when not meeting the challenge of sustainability (Stringer et al., 2020).

This study will cover the first three steps of an MCA analysis according to Abebe and Megento (2017), that include (1) set the goal/definition of the problem, (2) determine criteria and indicators and (3) standardize the indicators. Steps (4) determine the weight of each indicator, (5) aggregate the indicators and (6) validate/verify are not included, as this is the first and explorative study into crises suitability of food systems' food security.

3 Results and Discussion

3.1 MCA: Evaluation criteria and its indicators for crisis suitability of food's systems

3.1.1 Step 1: Goal of the project

The goal of the project is to develop a first framework of criteria and its indicators on the basis of which information can be gathered which ultimately could lead to decisions about crises suitability of food systems. This includes its suitability for immediate effective crises or for evolving crises. The framework is of a general nature and fine-tuned towards protein supply.

3.1.2 Step 2: Determine criteria and its indicators

The concept crises suitability of food systems was covered by criteria and indicators which ensure validity, measurability and efficiency in measuring. Key concepts used were food security, food system and crises. As a starting point for the operationalization of the concept crises suitability of food systems, the three aspects of food security were used, namely food availability, utilization, and access (FAO, 2006), since these are related to system thinking and the intrinsic value of food for people. These three aspects of food security are the base for the development of four criteria (a principle on which something is decided upon) and developing from that indicators, the measurable units. Based on these three aspects of food security, four main criteria were derived that are linked to the crisis suitability of food systems:

Aspects of food security	Criteria to evaluate crises suitability of food systems
Food availability	Production characteristics
Food utilization	Intrinsic attributes
Food access	Supply chain
	Feasibility of conversion

As linked to "*food availability*", as a first criterion efficient production characteristics covers production activities as a base requirement for food supply to the consumer (Barbosa et al., 2015; Grófová & Srnec, 2012). The second main criterion covers the intrinsic attributes of a food as linked "*food utilization*", relevant upon consumption of the food (Douglas et al., 2020; Lane et al., 2013; Perchonok & Bourland, 2002). In the food security aspect "*access*" to the food system, as a third criterion efficiency of the supply chain (Engelseth, 2016; Van Wassenhove, 2006) is included to enable people to receive the offer of foods. As a second element of "access", we distinguished as a fourth criterion feasibility of conversion to crises food production (Engelseth, 2016; Van Wassenhove, 2006) to highlight the speed of adaptation of the system to crises circumstances covering the threat of a potential distortion of receiving the offered food. This element is triggered by the divergent time constraints of different types of crises related to food security. This allows to differentiate between the suitability of a food system for immediate effects of a crisis on food security and for expected effects of a crisis developing over a longer period. For the latter, the crisis suitability of the food system is determined by room to improve elements of the food system. The first mentioned type of crisis determines the food system by its immediate response to support undisrupted food security.

The costs of implementing new food productions were not included in this research, because of their fluctuating nature over time (Stringer et al., 2020). In fact, Terluin et al. (2013) demonstrated that governments are expected to step in to support the expenses of the transition towards more efficient production in times of crisis, which especially counts for immediate crises.

Availability: production characteristics and its indicators First, a food requires efficient production characteristics to ensure food availability (Barbosa et al., 2015; Grófová & Srnec, 2012). Efficient production characteristics were described as the combination of high yield productivity and low production requirements, which is fundamental in case of crisis conditions (Grófová & Srnec, 2012). Yield productivity was defined as the time required to produce a certain amount of a food (Grófová & Srnec, 2012). The indicator identified to measure the yield productivity was the number of grams of proteins that could be produced per square meter per day, and labeled as *protein yield*. According to Barbosa and colleagues (2015), the production requirements of a food were divided into three categories, which were the amount of land, water, and energy a food required to produce a certain amount of product. While the functional unit used in most studies was based on the requirements to produce one kilogram of food (James & Boriah, 2010; Smetana et al., 2015; Tuomisto & Teixeira de Mattos, 2011; Tuomisto et al., 2014), the functional unit used in this research was the amount of resources necessary to produce one kilogram of protein of a food. Therefore, the indicators to measure the production requirements of a food were the number of square meters needed to produce one kilogram of proteins daily, the liters of water needed to produce one kilogram of protein, and the megajoules needed to produce one kilogram of protein. These were respectively labeled as *land-requirements*, *water-requirements*, and *energy-requirements*.

Utilization: intrinsic attributes and its indicators Second, food requires good intrinsic attributes to ensure food utilization (Douglas et al., 2020; Lane et al., 2013; Perchonok & Bourland, 2002). Intrinsic attributes can be divided into five categories: safety, health, sensory, shelf life, and convenience (Luning & Marcelis, 2011). It was demonstrated that foods which are safe, highly nutritious, highly palatable, with a long shelf life, and easy to use were critical to overcome a crisis situation (Douglas et al., 2020; Lane et al., 2013; Perchonok & Bourland, 2002). With the European Regulation 2015/2283 on Novel Foods, alternative protein sources were recognized as generally safe to consume. Nevertheless, the risk of hazards affecting the safety of alternative protein sources is still present and varies depending on the food. Hazards affecting the safety of a food can be of biological, chemical, or physical nature (Luning & Marcelis, 2011). The indicators identified for the riskiness to safety were *biological safety, chemical safety,* and *physical safety,* and were measured based on the risks of biological, chemical, and physical hazards affecting the safety of the food (Derbyshire & Ayoob, 2019; Post & Hocquette, 2017; Van der Weele et al., 2019; Van Huis et al., 2013).

Health, as an intrinsic attribute, refers to the nutritional value and satiation of a food (Luning & Marcelis, 2011). While meeting the daily recommended food intakes was important to avoid nutritional deficiencies, including vitamins and minerals such as vitamin B6, B12, iron and zinc, sufficient energy and protein intakes were identified as the most crucial components of the diet to ensure a well-functioning of all body functions (Lane et al., 2013; Perchonok & Bourland, 2002). To measure the energy content of food, the number of kilocalories per 100 grams was used (Tuomisto et al., 2014; Van der Weele et al., 2019; Van Huis et al., 2013). The indicator was labelled as *kilocalories*. To evaluate the protein profile of a food, the amount of protein, the amino acid profile, and the digestibility of the amino acids were identified (Alexander et al., 2017; Boland et al., 2013). These three components were identified as the indicators for the protein profile, and labeled as *protein content, amino acid profile,* and *protein digestibility*. The amount of protein in a food was measured through the grams of protein per 100 grams of a food (Churchward-Venne et al., 2017; Derbyshire & Ayoob, 2019; Van Huis et al., 2013). The amino acid profile was evaluated through the amount of the nine essential amino acids per 100 grams of total weight of a food (Boland et al., 2013; Wu et al., 2013). The availability and digestibility of the amino acids was measured with the PDCAAS (Schaafsma, 2005).

Sensory intrinsic attribute refers to the sensory attributes that influenced the palatability of a food, which include texture, smell, taste, appearance, and sound (Luning & Marcelis, 2011). Highly palatable foods are essential to ensure sufficient nutritional intake, as the portions of foods with low palatability could occasionally not be consumed, even under crisis conditions (Douglas et al., 2020; Smith, 2009). Moreover, the consumption of food could also be limited by other factors, as food neophobia (Barrena & Sánchez, 2013). Therefore, the indicators identified to evaluate the sensory intrinsic attribute were *palatability* and *consumer acceptance*. The palatability of a food was measured using the ratings it was assigned in sensory tests (Caparros Medigo et al., 2016; Finnigan et al., 2017; Hellwig et al., 2020). Consumer acceptance was evaluated based on the presence of factors which could have limited the consumption of a certain food (Post & Hocquette, 2017; Van der Weele et al., 2019; Van Huis et al., 2013).

Shelf life was defined as "the time during which the food product will remain safe, keep desired sensory, chemical, physiological and microbiological characteristics, and comply with any label declaration of nutritional data" (Luning & Marcelis, 2011). Under crisis conditions, foods with a longer shelf life are preferred, as it was demonstrated at the beginning of the COVID-19 pandemic (Toffolutti et al., 2020). The storage temperature of a food was crucial under crisis conditions, as closely linked to the shelf life length and as it could lead to complications; a food restricted to cold or frozen storage had to face issues, *e.g.,* space management, compared to foods which could be stored at room temperature (Douglas et al., 2020; Perchonok & Bourland, 2002). The indicators identified to evaluate the shelf life of a food were thus *shelf life time* and *shelf life temperature*. Shelf life time was measured with the number of days a food could be stored safely, and shelf life temperature with the type of storage required – room temperature, cold storage, frozen storage - (FAO, 2016; Finnigan et al., 2017; Tyner, 2020; Van Huis et al., 2013).

Convenience intrinsic attribute refers to the ease of preparation and use of a product, divided into physical and mental effort (Luning & Marcelis, 2011). Physical effort includes the time required to prepare a food, the complexity of the recipe, the complexity of cooking equipment, etc. (Douglas et al., 2020). Mental effort includes the knowledge of recipes, the existence of cookbooks, etc. (Douglas et al., 2020). According to Douglas and colleagues (2020), a product easy to prepare and use was identified as more suitable to improve food security under crisis conditions. The indicators identified for convenience intrinsic attributes were therefore the *physical effort* and *mental effort* required to prepare and use a food.

Access: supply chain efficiency and its indicators Third, food requires a production and distribution that relies on an efficient supply chain to ensure food access (Engelseth, 2016; Van Wassenhove, 2006). Food access includes two major components: economic access and physical access (Schwartz et al., 2019). However, as discussed by Terluin et al. (2013), local governments can be expected to economically support their citizens if a crisis had to emerge. For this reason, this research focused exclusively on physical access to food. An efficient supply chain is crucial under crisis conditions to ensure a continuous production (Engelseth, 2016; Van Wassenhove, 2006). Shortening the supply chain was demonstrated to be the optimal method to increase its efficiency, as fewer actors were required in the production of a food and as its complexity was reduced (Engelseth, 2016; Van Wassenhove, 2006). The length and complexity of the supply chain were thus identified as the main components of the supply chain. To measure the length of the supply chain, the number of actors involved in the production of a food, from the supply of the raw materials to the consumer were determined. This indicator was labeled *number of actors*. To assess the complexity of the supply chain, the complexity to access raw materials (Modrak et al., 2018) and the complexity to access consumers (Van Wassenhove, 2006) were used as indicators, and labeled as *access to raw materials* and *access to consumers*. The complexity to access raw materials was determined by the number of raw materials required for the production of a food and their availability (Modrak et al., 2018). The complexity to access consumers is measured by the distance between the place a food is produced and where the consumers live. As fuel shortages could be expected under crisis conditions (Terluin et al., 2013), being able to potentially produce food at walking or biking distance from the consumers reduces its complexity.

Access: conversion towards crisis food production and its indicator A food requires a feasible conversion from conventional to crisis food production (Stringer et al., 2020). Food productions with a high feasibility of conversion, which was described as the ability to rapidly shift from a conventional to crisis food production, were considered essential under crisis conditions (Stringer et al., 2020). The speed of conversion of a food production was influenced by the knowledge (Van Huis et al., 2013) and the technology (Stringer et al., 2020) required to produce a food. Food which requires no specific knowledge or technology was considered more suitable under crisis conditions, as it could be produced by anyone and with no specific means. The indicators identified for the feasibility of conversion were thus *knowledge required* and *technology required*. The knowledge required was measured based on the level of education necessary to produce a certain food, while the technology was measured based on its availability (Melgar-Lalanne et al., 2019; Van der Weele et al., 2019; Van Huis et al., 2013).

Figure 1 shows a visual representation of the criteria and indicators developed for each food security aspect.

3.1.3 Step 3: standardize indicators

In this explorative study, standardization is inserted by comparing the scores of the suitability indicators for the

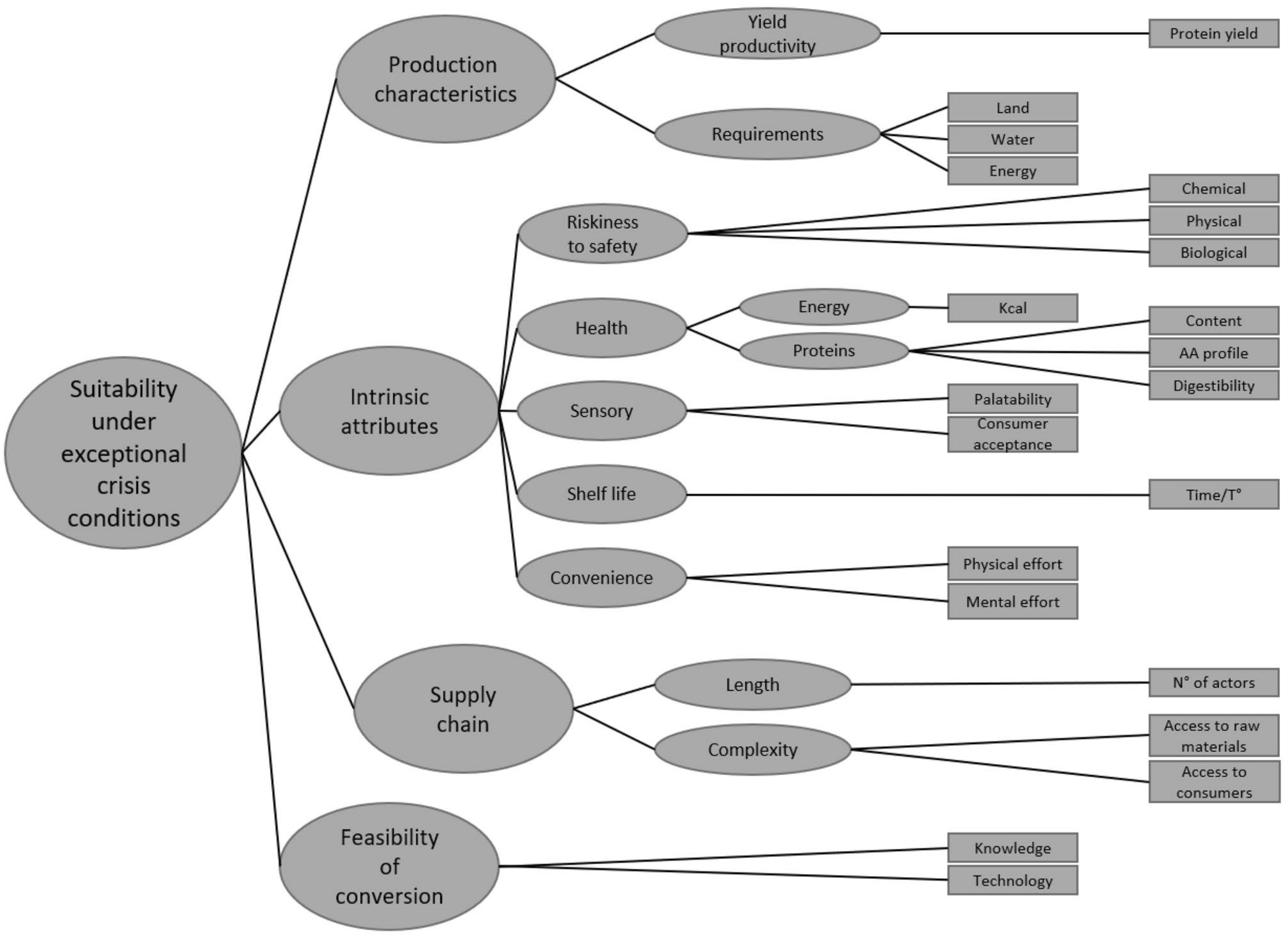

Fig. 1 Criteria and their indicators on the crises suitability of food system's food security

alternative protein sources to scores of chicken meat, that served as a reference values. Hence, a strict, generic standardization of the indicators in the sense of a uniform dimension of crisis suitability has not been developed. In this explorative study, standardization is inserted by comparing the scores of the suitability indicators for the alternative protein sources to scores of chicken meat, that served as a reference values. Hence, a strict, generic standardization of the indicators in the sense of a uniform dimension of crisis suitability has not been developed.

3.2 Crisis suitability of alternative proteins systems' food security

Alternative protein sources were compared to chicken meat based on the indicators previously identified to assess if, and which, alternative protein sources could be a viable option to embed in the food supply to improve food security under crisis conditions. The values of the indicators of chicken meat were presented in Table 4 of the Supplementary information. The data were presented according to the setup of Fig. 1.

3.2.1 Availability: Production characteristics related data

Table 1 shows the values of each alternative protein source and chicken meat for the production characteristics' indicators. The precise calculation can be found in Tables 5, 6, 7, 8, 9, and 10 of the Supplementary information.

While mealworms could be produced in similar quantities compared to chicken meat (Cadinu et al., 2020), the capability of cultured meat and mycoproteins to produce large amount of biomass largely exceeded the yield of chicken meat and of the other alternative protein sources. In fact, between 600 to 800 grams per square meter per day (Van der Weele & Tramper, 2014) and 12,500 grams per square meter per day (Derbyshire & Ayoob, 2019) could be produced by growing cultured meat and mycoproteins, respectively. Opposingly, the yield of algae and pulses was considerably lower compared to chicken meat; one to eight grams of proteins could be produced per square meter per day by growing algae (Koyande et al., 2019; Putt et al., 2011; Van Krimpen et al., 2013), while less than one gram per square meter per day was calculated for pulses based on data from Van Krimpen and colleagues (2013).

Table 1 Production characteristics' values of chicken and alternative protein sources with respect to protein yield, land requirement, water requirement and energy requirement

	Chicken	Insects	Cultured meat	Algae	Mycoproteins	Pulses
Protein yield (g/m2/day)	70 - 300 *(Allouche et al., 2015; Da Silva et al., 2014)*	145 *(Cadinu et al., 2020)*	600 - 800 *(Van der Weele & Tramper, 2014)*	1 - 8 *(Koyande et al., 2019; Putt et al., 2011)*	12 500 *(Derbyshire & Ayoob, 2019)*	0.08 - 0.75 *(Van Krimpen et al., 2013)*
Land requirement (m2/kg of protein)	3.3 - 14.3 *(Koyande et al, 2019; Mir et al., 2019)*	1/3 of chicken *(Cadinu et al., 2020)*	1.25 - 1.6 *(Van der Weele & Tramper, 2014)*	250 - 1000 *(Koyande et al., 2019; Putt et al., 2011)*	0.08 *(Derbyshire & Ayoob, 2019)*	1300 - 12 500 *(Van Krimpen et al., 2013)*
Water requirement (l/kg of protein)	70 -83 *(Manning et al, 2007; Smetana et al., 2015)*	0 - 6.5 *(Smetana et al., 2015; Dunkel & Payne, 2016)*	Lower than chicken *(Tuomisto & Teixeira de Mattos, 2011)*	400 000 - 800 000 *(James & Boriah, 2010)*	350 *(Smetana et al., 2015)*	0 *(Ding et al., 2018)*
Energy requirement (MJ/kg of protein)	78 - 128 *(Sefat et al., 2014; Tuomisto & Teixeira de Mattos, 2011)*	40 - 50 *(Smetana et al., 2015)*	113 - 183.5 *(Tuomisto, 2010)*	Lower than chicken *(Tuomisto, 2010)*	330 *(Tuomisto, 2010)*	Lower than chicken *(Van der Weele et al., 2019)*

The values for alternative protein sources which were more favourable than those of chicken meat were marked in green, when similar to chicken meat in yellow, and red was used for less favourable values than for chicken

Additionally, cultured meat and mycoproteins required less space to produce the same amount of proteins daily compared to chicken meat. Due to the possibility to grow insects vertically (Dunkel & Payne, 2016), the land-requirements of mealworms were also lower than chicken meat. In fact, Cadinu and colleagues (2020) demonstrated that mealworms required one third of the space of chicken to produce the same amount of proteins. Algae and pulses required respectively between 250 and 1000 square meters and between 1300 and 12 500 square meters to produce one kilogram of proteins daily compared to chicken meat which required between 3.3 and 14.3 square meters.

Mealworms and pulses had the lowest water-requirements, compared to chicken meat and the other alternative protein sources. In fact, while Smetana and colleagues (2015) discussed that mealworms required between 5.5 and 6.5 liters of water to produce one kilogram of protein, mealworms were demonstrated to be resistant to droughts (Van Huis et al., 2013) and could potentially grow without any additional water to the one in their feed (Dunkel & Payne, 2016). Similarly, while pulses required on average around 300-400 millimeters of water per year to grow efficiently (Ding et al., 2018), annual precipitations in Europe do not fall below 250 millimeters per year (Panagos et al., 2015). Therefore, even in case of low annual precipitations, only a minimal addition of water was required to ensure an efficient production of pulses. For this reason, pulses could basically be grown without additional water to the one provided by the rain. Cultured meat required more water than mealworms and pulses (Tuomisto & Teixeira de Mattos, 2011), however, Tuomisto and Teixeira de Mattos (2011) demonstrated through a life cycle assessment of chicken meat and cultured meat that the production of cultured meat required less water than chicken meat to produce the same amount of proteins. The water-requirements of mycoproteins were four to five times higher than chicken meat, as they required around 350 liters to produce one kilogram of proteins (Smetana et al., 2015). The water required to produce one kilogram of algae proteins, even if it could be re-used for other production cycles, was considered higher than chicken meat, as between 400 000 to 800 000 liters of water were required per kilogram of protein (James & Boriah, 2010).

Despite being the alternative protein sources with the highest yield, cultured meat and mycoproteins required considerably more energy compared to chicken meat and to the other proteins sources. Mycoproteins had the highest energy-requirements, as 330 Megajoules were needed to produce one kilogram of protein (Tuomisto, 2010). Mealworms, algae, and pulses required less energy than chicken meat. For example, Smetana and colleagues (2015) demonstrated that insects required around 40 to 50 Megajoules to produce one kilogram of proteins. Life cycle assessments of the production of algae (Tuomisto, 2010) and pulses (Van der Weele et al., 2019) concluded that these two alternative protein sources had also lower energy-requirements than chicken, but no qualitative analyses were performed.

In summary, mealworms resulted as a good alternative protein source to chicken as regard to the production characteristics, with all their indicators rated as similar or superior to chicken meat. The production characteristics of cultured meat were clearly superior to chicken meat, except for the energy-requirements. Mycoproteins could be produced in large quantities and had low land-requirements, but required considerably more water and energy compared to chicken meat. Opposingly, pulses had low requirements on water and energy needed, but their yield was the lowest compared to all protein sources. Algae, except for its low energy-requirements, did not present efficient production characteristics compared to chicken meat.

3.2.2 Utilization: Intrinsic attributes related data

All alternative protein sources were considered overall safer compared to chicken meat. In fact, except for cultured meat which was expected to be biologically equivalent to conventional meat (Bhat & Fayaz, 2011; Chavhan et al., 2020; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020), the prevalence of allergic reactions in sensitive patients caused by the consumption of insects (Turk et al., 2021; Van Huis, 2016), mycoproteins (Derbyshire & Ayoob, 2019; Finnigan et al., 2017; Wiebe, 2002), algae (Wells et al., 2017), and pulses (Bessada et al., 2019; Boye et al., 2010) were lower than chicken meat. Despite presenting similar risk of causing allergic reactions, cultured meat was considered chemically safer than chicken meat as no antibiotics or other chemicals were used in its production (Bhat & Fayaz, 2011; Chavhan et al., 2020; Post & Hocquette, 2017; Tyner, 2020; Wurgaft, 2020).

Moreover, while the physical safety of mycoproteins (FSA, 2019) and pulses (Singh, 2013; Sokhansanj & Patil, 2003) presented the same risks to be affected by foreign matters compared to chicken meat, the risks for insects (Makkar et al., 2014; Van Huis et al., 2013), cultured meat (Alexander et al., 2017; Bhat & Fayaz, 2011; Chavhan et al., 2020; Post & Hocquette, 2017; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020), and algae (Becker, 2007) were lower.

The risks of the alternative protein sources to be affected by biological hazards were also considered lower than chicken, including cultured meat. In fact, despite being biologically equivalent to conventional meat and thus potentially affected by similar biological hazards, the risks of cultured meat were reduced due to its production under aseptic conditions (Bhat & Fayaz, 2011; Chavhan et al., 2020; Post & Hocquette, 2017). The other alternative protein sources were also considered as biologically safer than chicken as all were processed; insects were generally powdered, which reduces the water availability and prevents microbiological growth (Melgar-Lalanne et al., 2019; Van Huis et al., 2013), pulses (Xipsiti et al., 2017) and algae (Bleakley & Hayes, 2017; Kovač et al., 2013; Vigani et al., 2015) dried, and mycoproteins fermented (Derbyshire & Ayoob, 2019; Wiebe, 2002).

As shown in Table 2, cultured meat was expected to be nutritionally equivalent to conventional meat (Bhat & Fayaz, 2011; Chavhan et al., 2020; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020), and therefore have identical number of kilocalories, protein content, digestibility, and amino acids profile to chicken meat. Pulses, even if variable depending on the species (Calles et al., 2019; USDA, 2023; Xipsiti et al., 2017) and algae (Alvarenga et al., 2011; Tang & Suter, 2011) also contained a similar number of kilocalories per 100 grams compared to chicken meat. Mealworms were the alternative protein source with the highest number of kilocalories per 100 grams (Cadinu et al., 2020; Dobermann et al., 2017; Van Huis et al., 2013). Opposingly, the number of kilocalories of mycoproteins was the lowest of all the proteins sources, as it was between, 80 and 90 kilocalories per 100 grams wet weight (Derbyshire & Ayoob, 2019; Finnigan, 2011; Finnigan et al., 2017; Trinci, 1992; Wiebe, 2002).

Moreover, except for mealworms which contained similar amount of proteins compared to chicken and cultured meat (Dunkel & Payne, 2016), the protein content of the other alternative protein sources was lower; it ranged for pulses between 17 to 40% dry weight (Bessada et al., 2019; Sharoba, 2014; Van Krimpen et al., 2013; USDA, 2023), around 11.25 and 11.5% for mycoproteins wet weight (Derbyshire & Ayoob, 2019; Finnigan, 2011; Finnigan et al., 2017), and between 25 to 50% dry weight for algae (Van Krimpen et al., 2013).

All alternative protein sources – mealworms (Ravzanaadii et al., 2012), mycoproteins (Finnigan et al., 2017; Coelho et al., 2020), algae (Bleaky & Hayes, 2017), and pulses (Day, 2013) – contained also overall lower quantities of the essential amino acids. Similarly, the protein digestibility of all alternative protein sources, except for mycoproteins (Finnigan et al., 2017; Coelho et al., 2020), was lower compared to chicken and cultured meat. According to different studies (Coelho et al., 2020; Edwards & Cummings, 2010; Finnigan, 2011; Pojić et al., 2018), the PDCAAS of mycoproteins could reach up to 99.6%. The protein digestibility of pulses was the lowest of all the protein sources, as its PDCAAS ranged from 46 to 73% (Nosworthy et al., 2017; Devi et al., 2018). Even if chitin could limit the protein digestibility of mealworms, it could potentially reach a high PDCAAS – up to 98% - (Churchward-Venne et al., 2017; Makkar et al., 2014; Mishyna et al., 2020; Van Huis et al., 2013).

While cultured meat was expected to have a similar taste to chicken (Bhat & Fayaz, 2011; Chavhan et al., 2020; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020), the alternative protein sources were also generally considered as palatable as chicken meat. For example, mealworms were rated in sensory tests with similar scores to chicken meat, as they obtained ratings between 6 and 6.5 on a 9-points hedonic scale (Caparros Medigo et al., 2016) and between 6

Table 2 Comparison of the nutritional values of the protein sources with respect to the amount of kilocalories, protein content, amino acid profile, and protein digestibility

	Chicken	Insects	Cultured meat	Algae	Mycoproteins	Pulses
Kilocalories	110-140 kcal/100g wet weight - 365-465g kcal/100g dry weight (Culioli et al., 2003; Smith et al., 1993; Strakova et al., 2012)	140-200 kcal/100g wet weight (Cadinu et al., 2020; Dobermann et al., 2017; Van Huis et al., 2013)	110-140 kcal/100g wet weight (Bhat & Fayaz, Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020)	370-428 kcal/100g dry weight (Alvarenga et al., 2011; Tang & Suter, 2011)	80-90 kcal/100g wet weight (Derbyshire & Ayoob, 2019; Finnigan, 2011; Finnigan et al., 2017; Trinci, 1992; Wiebe, 2002)	Chickpeas 360kcal, fava beans 320-36kcal, peas 340kcal, lupines 325-370kcal /100g dry weight (Calles et al., 2019; USDA, n.d.; Xipsiti et al., 2017)
Protein content	18 - 23% wet weight or 65 - 70% /100g dry weight (Culioli et al., 2003; Koyande et al, 2019; Mir et al., 2019)	Mealworms: 20.9% wet weight (Dunkel & Payne, 2016)	18-23%/100g wet weight (Bhat & Fayaz, Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020)	25-50% dry weight (Spirulina 71%) (Van Krimpen et al., 2013)	11.25-11.5% wet weight (Derbyshire & Ayoob, 2019; Finnigan, 2011; Finnigan et al., 2017)	Fava beans: 26% - Chickpeas: 17-22% - Lupines 40% - Peas: 19-23% /100g dry weight (Bessada et al., 2019; Sharoba, 2014; Van Krimpen et al., 2013; USDA, n.d.)
Amino acids profile (g/100g dry weight)	Histidine 4.5; isoleucine 3.24; leucine 6.4; lysine 7.88-7.9; methionine 2.5-2.55; phenylalanine 3.18-3.2; threonine 3.7; valine 3.46; tryptophan 0 (Koyande et al, 2019; Hascik et al., 2020)	Histidine 1.5; isoleucine 3.56; leucine 3.4; lysine 2.9; methionine 0.67; phenylalanine 1.17; threonine 1.8; valine 2.5 (Ravzanaadii et al., 2012)	Histidine 4.5; isoleucine 3.24; leucine 6.4; lysine 7.88-7.9; methionine 2.5-2.55; phenylalanine 3.18-3.2; threonine 3.7;tryptophan 0; valine 3.46 (Bhat & Fayaz, Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020)	Histidine 1.1; isoleucine 3.3; leucine 4.9; lysine 2.4; methionine 1.25; phenylalanine 2.7; threonine 3.6; tryptophan 0.15; valine 3.5 (Bleaky & Hayes, 2017)	Histidine 1.6-1.7, isoleucine 2.4-2.6, Leucine 3.9-4.3, Lysine 3.8-4.1, methionine 1, phenylalanine 2.3-2.9, threonine 2.5-2.7, tryptofan 0.8, valine 2.8-3.6 (Finnigan et al., 2017; Coelho et al., 2020)	Histidine 0.7, isoleucine 1, leucine 1.95, lysine 1.77, methionine 0.27, phenylalanine 1.5, threonine 0.97, tryptophan 0.22, valine 1.17 (Day, 2013)
Protein digestibility (PDCAAS)	88 - 92% (Hascik et al., 2020; Pereira & Vicente, 2013; Soriano-Santos, 2010)	70-98% (Makkar et al., 2014; Mishyna et al., 2020; Van Huis et al., 2013)	88-92% (Bhat & Fayaz, Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020)	76-77% - Up to 89% for Chlorella (Bleaky & Hayes, 2017)	91-99.6% (Coelho et al., 2020; Edwards & Cummings, 2010; Finnigan, 2011; Pojić et al., 2018)	46-73% (Nosworthy et al., 2017; Devi et al., 2018)

and 8 on a 10-points hedonic scale (Caparros Medigo et al., 2014). Boiled mealworms, however, obtained a lower rating in this latter study. Burgers made from mycoproteins were rated in another study with scores between 3 and 4 on a 5-points hedonic scale (Hellwig et al., 2020). Holliday (2014) evaluated the overall liking of burgers made with pulses, which obtained a score of 3.9 on a 5-points hedonic scale. In another sensory test (García-Segovia et al., 2020), breadsticks made with algae powder were rated 6.3 on a 9-points hedonic scale. However, it was demonstrated that algae could only be used in small amount as excessive quantities gave unpleasant color and taste to the product they were integrated in (Özyurt et al., 2015).

Despite having a similar taste to chicken meat, certain alternative protein sources had to face challenges to meet consumer acceptance. In fact, it was demonstrated that the consumption of cultured meat was limited by a perceived unnaturalness (Alexander et al., 2017; Bhat & Fayaz, 2011; Chavhan et al., 2020; Post & Hocquette, 2017; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020) and the consumption of insects by neophobia and disgust (Dunkel & Payne, 2016; Melgar-Lalanne et al., 2019; Mishyna et al., 2020; Van Huis, 2016; Van Huis et al., 2013). Additionally, European consumers were not familiar with algae due to the limited consumption on the continent, thus limiting the acceptance (Bleakley & Hayes, 2017; Grahl et al., 2020; Vigani et al., 2015). Opposingly, pulses (Calles et al., 2019; Day, 2013; Van der Weele et al., 2019; Xipsiti et al., 2017) and mycoproteins (Finnigan et al., 2017; Hellwig et al., 2020) were widely accepted by the consumers. However, it was demonstrated that humans quickly overcome unpleasant taste and disgust when food starts to become scarce (Hoefling & Strack, 2010); food deprived people tend to prefer an immediate source of nutrient over selecting a preferred food.

While cultured meat, as chicken, could be stored between six to ten days at refrigerated temperatures, its shelf life could reach up to one year at -18 degrees Celsius (Tyner, 2020; Wurgaft, 2020). The shelf life of mycoproteins varied based on the product it was integrated in, but refrigerated or frozen storage was required (Finnigan, 2011; Finnigan et al., 2017; Trinci, 1992). For example, most Quorn™ products, which are made from mycoproteins, had a similar shelf life compared to chicken meat, as they could be stored for one year at – 18 degrees Celsius or a couple of weeks at refrigerated temperatures. Mealworms, algae, and pulses had a long shelf life and did not require refrigeration, as they were dried. In fact, powdered insects could be stored at room temperature for seven months according to Kamau and colleagues (2018), while Van Huis and colleagues (2013) affirmed their shelf life could be up to one year. Similarly, the shelf life of algae powder was 258 to 263 days at 30 degrees Celsius (Tiburcio et al., 2007). As for pulses, it was demonstrated that they could be stored for several years at room temperature (FAO, 2016).

As generally used as powder, algae (Bleakley & Hayes, 2017; Grahl et al., 2020; Vigani et al., 2015) and insects (Melgar-Lalanne et al., 2019; Van Huis et al., 2013) required time and knowledge to be integrated into recipes, which increased both the mental and physical effort required for their preparation. Pulses required soaking and heating before consumption, when dry, to eliminate the antinutritional compounds they contained, thus considerably increasing the physical effort required to use them (Bessada et al., 2019; Havemeier et al., 2017). Moreover, even if consumers generally preferred processed and canned pulses (Schneider, 2002), thus not requiring a soaking and cooking step, the mental effort needed to prepare pulses remained high. This is due to the limited practical knowledge consumers have about the cooking process and to the type of ingredients pulses can be associated in a meal preparation (Melendrez-Ruiz et al., 2019). Opposingly, mycoproteins, as chicken and cultured meat, only required a single cooking step and no mental effort to prepare and use (Trinci, 1992; Wiebe, 2002).

3.2.3 Access: Supply chain efficiency related data

Pulses and insects were the alternative protein sources with the simpler supply chains; three actors were required for their production at large scale, namely the suppliers of seeds or feed, the producers, and the consumers. Furthermore, both pulses (Calles, 2016; Day, 2013; Terluin et al., 2013) and insects (Dunkel & Payne, 2016; Melgar-Lalanne et al., 2019; Van Huis et al., 2013) could easily be grown at home, further reducing the number of actors in the supply chain to one and facilitating the access to the consumers. Moreover, both alternative protein sources could leverage of accessible raw materials as pulses only required the seeds, which are easily replicable (Terluin et al., 2013), while insects could be fed exclusively with food or forest by-products (Dunkel & Payne, 2016; Madau et al., 2020; Melgar-Lalanne et al., 2019; Van Huis et al., 2013).

Due to the processing required, the production of mycoproteins (Finnigan, 2011; Finnigan et al., 2017; Wiebe, 2002), algae (Bleakley & Hayes, 2017; Wells et al., 2017), and cultured meat (Post & Hocquette, 2017; Van der Weele & Tramper, 2014) included one more step – the processing – in addition to supplying raw materials, producing, and delivering to consumers. The processing included the transformation into the final product for the consumer – as burgers, for example - for cultured meat and mycoproteins, and drying and grinding for algae. Nevertheless, the raw materials required to produce mycoproteins and algae were easily accessible, as mycoproteins required a sugar source – wheat, grapes, etc. - (Finnigan, 2011; Finnigan et al., 2017; Souza Filho et al., 2019; Trinci, 1992; Wiebe, 2002) and algae required water and basic nutrients (Adeniyi et al., 2018; Bleakley & Hayes, 2017; Demirbas, 2010). Obtaining the raw material required for the production of cultured meat – the growth medium -, however, was complex (Alexander et al., 2017; Van der Weele et al., 2019; Van der Weele & Tramper, 2014; Wurgaft, 2020). Despite a more complex supply chain compared to pulses and insects, cultured meat (Bhat & Fayaz, 2011; Van der Weele & Tramper, 2014) and mycoproteins (Wiebe, 2002) could potentially be produced anywhere, even in urban areas. Algae could also be produced potentially anywhere, however, a large space was required to install raceway ponds (Bleakley & Hayes, 2017; Kovač et al., 2013) therefore limiting its access to the consumers.

3.2.4 Access: Feasibility of conversion related data

Insects, pulses, and algae were identified as the alternative proteins sources with the highest feasibility of conversion, as the knowledge and technology required for their production was low. In fact, it was demonstrated that rearing insects was very simple and required no, or minimal, training (Hwang & Choe, 2020; Madau et al., 2020; Van Huis et al., 2013). Additionally, only basic and easily accessible technology was required – as plastic containers - (Melgar-Lalanne et al., 2019). The same applied for pulses, as they could be cultivated by anyone, without particular skills or training (Calles, 2016; Calles et al., 2019; Terluin et al., 2013; Van der Weele et al., 2019), and could be achieved without any technology (Bessada et al., 2019; Bleaky & Hayes, 2017; Calles, 2016; Calles et al., 2019; Day, 2013; Terluin et al., 2013; Van der Weele et al., 2019). According to Adeniyi and colleagues (2018), the production of algae did not require in-depth training either, as its supervision and maintenance was simple. It also required basic, cheap, and accessible technology to operate (Adeniyi et al., 2018; Demirbas, 2010; Vigani et al., 2015); paddles to ensure a constant flow of the water and homogenization of the nutrients were the only technological requirement for the production of algae (Adeniyi et al., 2018; Demirbas, 2010).

Opposingly, cultured meat and mycoproteins could only be produced by highly trained and expert workers. In fact, scientists and engineers – as food technologists, tissues engineers, etc. – were the principal actors in the production of cultured meat (Bhat & Fayaz, 2011; Post & Hocquette, 2017; Van der Weele & Tramper, 2014; Wurgaft, 2020). Similarly, strict and precise values of temperature, pH, oxygen, and nutrients were needed to be maintained to achieve an efficient production of mycoproteins, thus requiring the supervision of experts (Finnigan, 2011; Trinci, 1992). Moreover, the production of both alternative protein sources required advanced technology. It was demonstrated that advanced bioreactors, scaffolds, sanitation machineries, etc. were needed to produce cultured meat (Bhat & Fayaz, 2011; Chavhan et al., 2020; Post & Hocquette, 2017; Tuomisto, 2010; Tuomisto et al., 2014; Van der Weele & Tramper, 2014; Wurgaft, 2020). Similarly, fermenters and air-lifting systems were required for an optimal production of mycoproteins (Coelho et al., 2020; Derbyshire & Ayoob, 2019; Finnigan, 2011; Finnigan et al., 2017; Trinci, 1992; Wiebe, 2002).

3.2.5 Assessing overall crisis suitability of alternative protein sources' food security

As illustrated in Fig. 2, the colour scheme elaborated in Section 3 was applied for each indicator of all alternative protein sources studied.

In Fig. 2, the overview is given for the suitability of alternative protein sources to act as a food stuff in times of crises. The crisis suitability is expressed in terms of more, similar or less suitable compared to chicken meat. Overall, the suitability of alternative protein sources shows that the scores on the indicators are such that none of the alternative protein sources is unambiguously better suitable for a crisis situation than chicken, although these are seen as promising substitutes for existing proteins. All alternative protein sources have pros and cons, compared to chicken, to act as a crisis food.

In the comparison of the alternative protein sources, the better performance of insects (Churchward-Venne et al., 2017; Van Huis, 2016; Van Huis et al., 2013) and cultured meat (Post & Hocquette, 2017; Tuomisto, 2010), was confirmed in this research although the latter studies were not crisis focussed and therefore didn't take into account all the crises suitability indicators investigated in this research. On the level of the overall concept 'crisis suitability', both insects and cultured meat were assessed on the majority of indicators as suitable as – or even more suitable than – chicken meat under crisis conditions. In fact, as shown in Fig. 2, the vast majority of their indicators were rated as more suitable or as suitable as chicken food system.

In detail, the supply chain of insects was rated as more suitable than chicken food system for all the indicators under crisis conditions, except for intrinsic attributes due to its amino acid profile, consumer acceptance, and convenience which were limited compared to chicken meat. Protein yield, protein content, and palatability were rated as suitable as chicken.

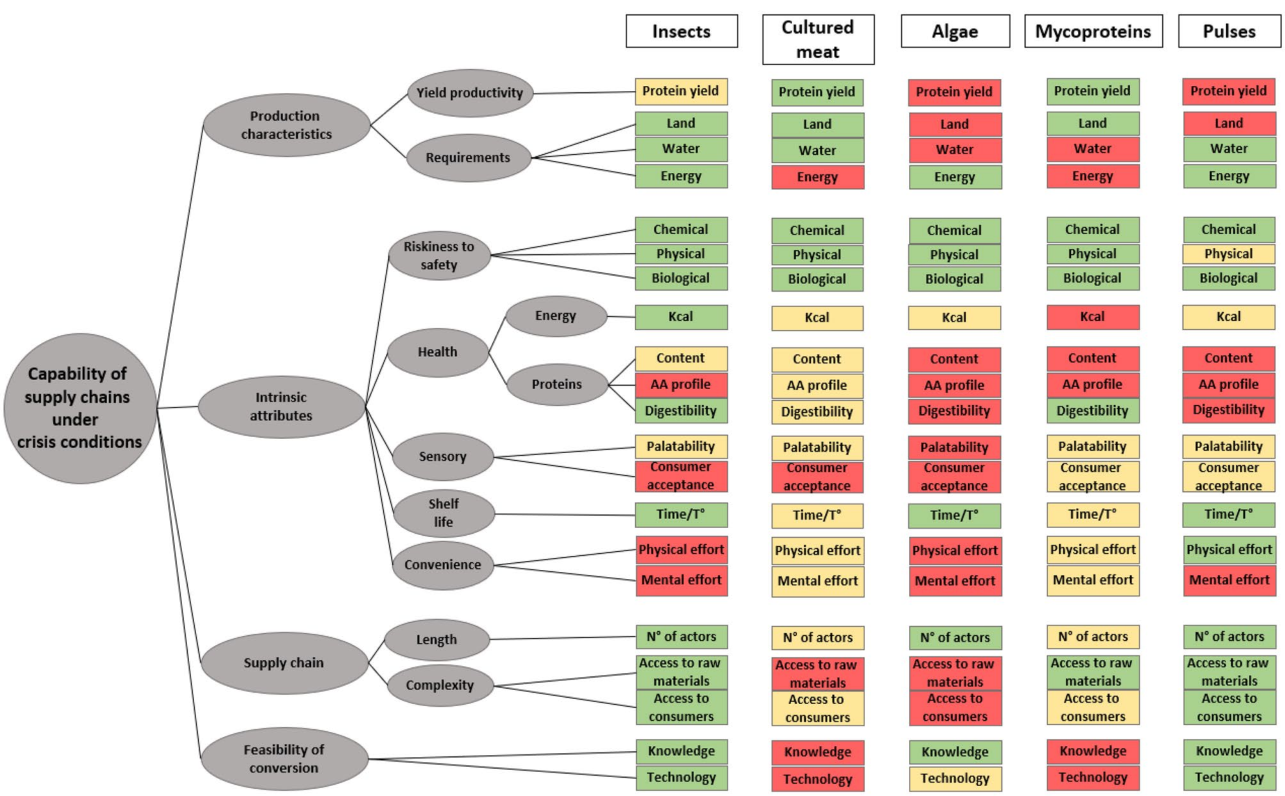

Fig. 2 Crises suitability of alternative proteins system's food security compared to chicken meat's crises suitability with respect to production characteristics, intrinsic attributes, supply chain efficiency and feasibility of conversion

The food system of cultured meat was mostly rated more suitable and as suitable as chicken based on the assumption of its expected biological and nutritional equivalence to conventional meat (Bhat & Fayaz, 2011; Chavhan et al., 2020; Tyner, 2020; Van der Weele et al., 2019; Wurgaft, 2020) and the assumption that it could be produced in larger quantities with lower requirements, except for the energy required. The feasibility of conversion, consumer acceptance, and access to raw materials were, however, less suitable than chicken food system.

Opposingly, even if studies (Calles, 2016; Calles et al., 2019; Day, 2013) demonstrated the potential of pulses to fight global food insecurity, it resulted that the suitability of pulses food system was less than the chicken food system when a crisis should occur. In fact, even if their requirements – except for space required –, supply chain, and feasibility of conversion were rated as more suitable than chicken food system under crisis conditions, the suitability of the pulses food system was highly limited by their low nutritional values and quantity that could be produced compared to chicken. Based on the indicators developed, the suitability of the food systems of mycoproteins and algae were also limited under crisis conditions compared to chicken meat. In fact, although mycoproteins were rated as more capable than and as suitable as chicken under crisis conditions due to their high yield productivity, safety, overall suitable intrinsic attributes, and supply chain, the capability of their supply chain was limited by the high production requirements, low nutritional values, and low feasibility of conversion. Algae produced in raceway ponds resulted as the alternative protein source the least capable of replacing chicken meat under crisis conditions as the majority of their indicators were rated as less suitable than chicken; even if algae could leverage on low energy-requirements, high safety, long shelf life and high feasibility of conversion, the suitability of the other indicators was limited compared to chicken meat. However, an innovative way to produce algae – through fermentation (Voloshin et al., 2016) – could improve the ratings assigned to algae produced in raceway ponds. Since this process was mostly used for the production of biofuels, no sufficient studies for the production of algae through fermentation for human food were available at the time this research was performed.

3.3 Further development of the concept crisis suitability

Through the example of alternative protein sources, this research laid the bases for the evaluation of crisis suitability of food systems, in order to develop in due time a tool to support policy decision making in this matter. As no specific studies exist to assess the crises suitability of food systems under crisis conditions, this research identified essential criteria of a food system under crisis conditions, which were the production characteristics, intrinsic attributes, supply chain efficiency, and feasibility of conversion. The insights based on the four criteria on crises suitability of food systems for food security enabled to discriminate between the alternative protein sources on the suitability of the food systems and can serve, when further developed according to the later steps of MCA, as an input for decision making.

Equal weighing of indicators In the overview of the results in Section 3.2, all indicators identified to assess the crisis suitability were considered equally relevant. However, in practice the relevance of certain indicators could vary. For example, palatability could become more relevant compared to other indicators in the case of a distasteful food, as people would not (directly) be inclined to eat it. Also, country specific characteristics could influence the weigth of indicators. For example, the importance of the water requirements indicator could possibly increase drastically in a country where water availability is scarce. Additionally, the relevance of certain indicators could also change based on the characteristics of the crisis, as it was presented in Table 3. For example, the possible crises that could occur in the Netherlands were influenza pandemics, extreme weather conditions, floods, solar storms, and droughts (RIVM, 2016), ranging from likely to take place to unlikely. If the availability of chicken meat had to be limited – as it could in case of avian flu pandemic –, an alternative protein source able to replace chicken could become essential, thus increasing the relevance of the indicators related to protein yield and nutritional values compared to the other indicators. In that case, cultured meat could become the most interesting alternative protein source to embed in the food supply chain as its nutritional values were the same as chicken and as it could be produced in large quantities.

Additionally, the indicators related to the supply chain could gain relevance under a crisis causing complications of movement, as moving goods and physically accessing the food could be limited. Complications with respect to transport are expected for extreme weather conditions or floods. Similarly, a disruption of the communication services, as for solar storms, could limit the collaboration of the actors in the supply chains of a food and giving an advantage to the alternative protein sources with fewer actors required. Under such circumstances, insects and pulses could become the most viable alternative protein sources as they could be produced directly by the consumer. A crisis affecting the availability of land or water, as is to be expected for floods or droughts, could possibly make the alternative protein sources with lower requirements more capable of replacing chicken meat. For example, if the space available to produce foods was limited, insects, cultured meat, and mycoproteins could possibly become the most viable protein sources to ensure food security best. Finally, floods and extreme weather conditions, which could cause damage to

Table 3 Likelihood, consequences, and indicators affected based on the different potential crises in the Netherlands

Crisis	Probability	Consequences	Criteria affected
Influenza pandemic*	Likely*	Limited availability of chicken meat	Protein yield
			Number of kilocalories
			Protein content
			Amino acids profile
			Protein digestability
Extreme weather*	Likely*	Damages on foodstuffs and raw materials produced outdoors	Access to raw materials
		Complications of movement	Number of actors
			Access to raw materials
			Access to the consumers
Flood*	Somewhat likely*	Less land available	Land-requirements
		Complications of movement	Number of actors
			Access to raw materials
			Access to the consumers
Solar storm*	Somewhat likely*	Disruption of communication	Number of actors
Drought*	Unlikely*	Less water available	Water-requirements

Information extracted from RIVM report (2016) were marked with *

the raw materials required for the production of food would also limit their availability and access.

This implies that determining crises suitability will be a process that needs to be tailored to the specific crisis situation and possibly to the (geographical) environment. Depending on specific contexts, decisions need to be made about the weighing of the several indicators and the reference food, which is meaningful in that environment. The assessment of the suitability will differ on the weight of importance of different indicators decision makers will give to them, and how these decision makers ultimately deal with the fact that crises suitability of food stuffs can contain indicators with conflicting values and the varying time constraints of the occurrence of crisis circumstances. These are issues that need to be dealt with in the steps of the MCA which were not under investigation in this research, *i.e.,* 4) determine the weight of each indicator, (5) aggregate the indicators and (6) validate/verify the results (see Section 2). In order to provide information about the weighing of indicators for the suitability of food systems under specific crises conditions within a specific (geographical) environment, research can be done. Specifically for food security provided by food systems, to our knowledge, no research has been done to get insight into its determinants. However, *e.g.,* food security on a country level has been researched by means of a quantitative research strategy (Sarkar et al., 2021) which could act as an example approach to get insights into the crises suitability criteria and its indicators.

However, considering the weighing of indicators in different circumstances and their potential conflicting values, the decisions made are essentially based on the information given by means of the framework designed in this research. This shows that the framework is a solid layer to gain insights for specific crisis, country, and food systems suitability.

Usage of the framework Also given the time constraints as a characteristic of each crisis, we derive two functions of this framework to be used in the practice of decision making. The first function is to be able to take decisions on the crises suitability of food systems (see Gésan-Guziou et al., 2020 for a decision-oriented type of research). This function is meant to prepare a country or region from the perspective of food security for crises that require immediate availability of foods with nutritional value as was worked out for alternatives protein sources. The second function that we foresee for this framework is that it can provide suggestions for improvement of certain food systems to be prepared for crises that can be foreseen for the longer term (see Blanco-Gutiérrez et al., 2020 for such a type of an evaluation study). In this manner, certain crises suitability criteria and indicators, when scoring lower than the reference, could be improved in such a manner that a food would become (more) crisis suitable. When preparing for decision taking, one should take into account that the information about the different indicators is dependent on further development, innovation for instance on species/strains/varieties, processing technologies, distribution modes (see Gésan-Guiziou et al., 2020). Hence, when certain types of innovation will occur and are adopted, the score of certain indicators will change, which has of course its influence on the crises suitability of the alternative protein sources. Next to that, indicator values assigned in this research could change in time. For example, the palatability and consumer acceptance of novel proteins could possibly become more suitable as new recipes and a decline in neophobia for certain novel proteins could occur over time. The temporality of the information implies continuous maintenance of the content of the framework.

Through the example of alternative protein sources, this research laid the bases for the evaluation of the crises suitability of foods systems through the development of a framework. To have a sound conceptual bases for multi-criteria research is emphasized by several other research (Gésan-Guiziou et al., 2020; Blanco-Gutiérrez et al., 2020; Sarkar et al., 2021). Such practice-oriented research is in its nature multi-disciplinary. A multi-disciplinary approach is needed to be able to study suitability of food system food security which entails knowledge about food technology, production/processing/distribution, supply chain management. Multi-disciplinarity is then needed to match the complexity of such availability of foods for people suffering from a crisis. Such a complex issue will lead to a complex decision-making process in which data on suitability of foods system needs to be assessed against the background of diverging circumstances as types of crises, time constraints of crisis, characteristics of a certain country/region, consumer preferences. Moreover, the values of the set of multi-disciplinary criteria can be potentially conflicting. However, as this set of criteria also represents a breakdown of the complex concept of crises suitability of food systems' food security, this framework can trigger further development of such a multi-disciplinary framework. Further research could be done by including the following steps of the MCA. This would mean that *e.g.,* policy makers would go through a simulation in which they are asked to take decisions on food when being confronted with a certain type of crises.

4 Conclusion

The insights gained through this research mark the first steps in developing an analysis tool to support policy decision making in pinpointing foods suitability to ensure food security under crisis conditions. To evaluate crises suitability of food systems, four criteria were identified, which were the production characteristics, intrinsic attributes, supply chain efficiency, and feasibility of conversion. These criteria adopted to the comparison of alternative protein sources showed a discriminatory potential. Detailed differences became apparent between the alternative protein sources. This underpins the usefulness of the concept crises suitability of food system to be used as input for policy discussions on alternative food supply in crisis situations.

Based on these criteria, it resulted that insects could replace chicken meat to ensure food security under crisis conditions, as most of the indicators of their supply chain were assessed as more suitable than chicken meat, in particular the indicators related to the production requirements, the supply chain efficiency, and the feasibility of conversion. Similarly, cultured meat was assessed as suitable to replace chicken under crisis conditions, as it could be produced in larger quantities while being nutritionally equivalent to conventional meat. The other alternative protein sources - mycoproteins, algae, and pulses – did not result as suitable to provide a source of protein to ensure food security under crisis conditions due to limitations in their systems. However, if a crisis had to occur, these alternative protein sources could help in providing an additional source of proteins by complementing chicken meat. The ratings assigned to each indicator of the alternative protein sources could, however, possibly require adjustments based on the type of crisis that occurs.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Abebe, M. T., & Megento, T. L. (2017). Urban green space development using GIS-based multi-criteria analysis in Addis Ababa metropolis. *Applied Geomatics*. https://doi.org/10.1007/s12518-017-0198-7

Adeniyi, O. M., Azimov, U., & Burluka, A. (2018). Algae biofuel: current status and future applications. *Renewable and Sustainable Energy Reviews, 90*, 316–335.

Alexander, P., Brown, C., Arneth, A., Dias, C., Finnigan, J., Moran, D., & Rounsevell, M. D. (2017). Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security, 15*, 22–32.

Alvarenga, R. R., Rodrigues, P. B., Cantarelli, V. D. S., Zangeronimo, M. G., Silva Júnior, J. W. D., Silva, L. R. D., ... & Pereira, L. J. (2011). Energy values and chemical composition of spirulina (Spirulina platensis) evaluated with broilers. *Revista Brasileira de Zootecnia, 40*, 992–996.

Amjath-Babu, T. S., Krupnik, T. J., Thilsted, S. H., & McDonald, A. J. (2020). Key indicators for monitoring food system disruptions

caused by the COVID-19 pandemic: Insights from Bangladesh towards effective response. *Food Security, 12*(4), 761–768.
Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health, 12*(6), 6879-6891.
Barrena, R., & Sánchez, M. (2013). Neophobia, personal consumer values and novel food acceptance. *Food Quality and Preference, 27*(1), 72–84.
Becker, E. W. (2007). Micro-algae as a source of protein. *Biotechnology Advances, 25*(2), 207–210.
Bessada, S. M., Barreira, J. C., & Oliveira, M. B. P. (2019). Pulses and food security: Dietary protein, digestibility, bioactive and functional properties. *Trends in Food Science & Technology, 93*, 53–68.
Bhat, Z. F., & Fayaz, H. (2011). Prospectus of cultured meat—advancing meat alternatives. *Journal of Food Science and Technology, 48*(2), 125–140.
Blanco-Gutiérrez I., Varela-Ortega, C., Manners, R. (2020). Evaluating animal-based foods and plant-based alternatives using multicriteria and SWOT analyses. *International Journal of Environmental Rese3arch and Public Health, 17*, 7969; doi:103390/ijerph17217969.
Bleakley, S., & Hayes, M. (2017). Algal proteins: extraction, application, and challenges concerning production. *Foods, 6*(5), 33.
Boland, M. J., Rae, A. N., Vereijken, J. M., Meuwissen, M. P., Fischer, A. R., van Boekel, M. A., ... & Hendriks, W. H. (2013). The future supply of animal-derived protein for human consumption. *Trends in Food Science & Technology, 29*(1), 62-73.
Boye, J., Zare, F., & Pletch, A. (2010). Pulse proteins: Processing, characterization, functional properties and applications in food and feed. *Food Research International, 43*(2), 414–431.
Cadinu, L. A., Barra, P., Torre, F., Delogu, F., & Madau, F. A. (2020). Insect Rearing: Potential, Challenges, and Circularity. *Sustainability, 12*(11), 4567.
Calles, T. (2016). The international year of pulses: what are they and why are they important. *Agriculture for Development, 26*, 40–42.
Calles, T., Xipsiti, M., & del Castello, R. (2019). Legacy of the international year of pulses. *Environmental Earth Sciences, 78*(5), 1–8.
Campbell, B. M. (2016). The great transition. Cambridge University Press.
Caparros Megido, R., Sablon, L., Geuens, M., Brostaux, Y., Alabi, T., Blecker, C., ... & Francis, F. (2014). Edible Insects Acceptance by B elgian Consumers: Promising Attitude for Entomophagy Development. *Journal of Sensory Studies, 29*(1), 14-20.
Caparros Megido, R., Gierts, C., Blecker, C., Brostaux, Y., Haubruge, É., Alabi, T., & Francis, F. (2016). Consumer acceptance of insect-based alternative meat products in Western countries. *Food Quality and Preference, 52*, 237–243.
Chavhan, D. M., Kumar, A., & Jat, R. C. (2020). An overview of In-vitro meat production and its limitations. *International Journal of Chemical Studies, 8*(4), 351–353.
Churchward-Venne, T. A., Pinckaers, P. J., van Loon, J. J., & van Loon, L. J. (2017). Consideration of insects as a source of dietary protein for human consumption. *Nutrition Reviews, 75*(12), 1035–1045.
Coelho, M. O., Monteyne, A. J., Dunlop, M. V., Harris, H. C., Morrison, D. J., Stephens, F. B., & Wall, B. T. (2020). Mycoprotein as a possible alternative source of dietary protein to support muscle and metabolic health. *Nutrition Reviews, 78*(6), 486–497.
Dagevos, H., & Voordouw, J. (2013). Sustainability and meat consumption: is reduction realistic?. *Sustainability: Science, Practice and Policy, 9*(2), 60-69.
Day, L. (2013). Proteins from land plants–potential resources for human nutrition and food security. *Trends in Food Science & Technology, 32*(1), 25–42.
Demirbas, A. (2010). Use of algae as biofuel sources. *Energy conversion and management, 51*(12), 2738–2749.
Derbyshire, E., & Ayoob, K. T. (2019). Mycoprotein: nutritional and health properties. *Nutrition Today, 54*(1), 7–15.
De Boer, J., & Aiking, H. (2011). On the merits of plant-based proteins for global food security: Marrying macro and micro perspectives. *Ecological economics, 70*(7), 1259–1265.
Devi, S., Varkey, A., Sheshshayee, M. S., Preston, T., & Kurpad, A. V. (2018). Measurement of protein digestibility in humans by a dual-tracer method. *The American Journal of Clinical Nutrition, 107*(6), 984–991.
Ding, D., Zhao, Y., Guo, H., Li, X., Schoenau, J., & Si, B. (2018). Water Footprint for Pulse, Cereal, and Oilseed Crops in Saskatchewan, Canada. *Water, 10*(11), 1609.
Dobermann, D., Swift, J. A., & Field, L. M. (2017). Opportunities and hurdles of edible insects for food and feed. *Nutrition Bulletin, 42*(4), 293–308.
Douglas, G. L., Zwart, S. R., & Smith, S. M. (2020). Space food for thought: Challenges and considerations for food and nutrition on exploration missions. *The Journal of Nutrition, 150*(9), 2242–2244.
Dunkel, F. V., & Payne, C. (2016). Introduction to edible insects. In *Insects as sustainable food ingredients* (pp. 1-27). Academic Press.
EC. (2023). *Approval of fourth insect as a Novel Food*. European Commission. Retrieved from https://food.ec.europa.eu/safety/novel-food/authorisations/approval-insect-novel-food_en
Edwards, D. G., & Cummings, J. H. (2010). The protein quality of mycoprotein. *Proceedings of the Nutrition Society, 69*(OCE4).
Engelseth, P. (2016). Developing exchange in short local foods supply chains. *International Journal on Food System Dynamics, 7*(3), 229–242.
Ericksen, P., Stewart, B., Dixon, J.,, Barling, D., Loring, P., Anderson, M., & Ingram, P. (2010). The value of a food system approach. In; *Food security and global environmental change*. Ingram, J., Ericksen, P. & Liverman, D. (eds). Earthscan, Londo, p.25-46.
FAO. (June 2006). Food Security, Policy Brief, Issue 2. Retrieved from https://www.fao.org/fileadmin/templates/faoitaly/documents/pdf/pdf_Food_Security_Cocept_Note.pdf
FAO. (2016). *Pulses contribute to food security*. Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a-i5387e.pdf
FAO, IFAD, UNICEF, WFP and WHO. (2020). *The State of Food Security and Nutrition in the World 2020.* Transforming food systems for affordable healthy diets. Rome, FAO. Retrieved from https://doi.org/10.4060/ca9692en
FSA. (2019). *Quorn Foods recalls Quorn Cocktail Sausages because they may contain small pieces of metal*. Food Standards Agency. Retrieved from https://www.food.gov.uk/news-alerts/alert/fsa-prin-35-2019
FSIN. (2022). *Global Report on Food Crises 2022 Mid-Year Update*. Food Security Information Network. Retrieved from https://reliefweb.int/report/world/global-report-food-crises-2022-mid-year-update

Finnigan, T. J. A. (2011). Mycoprotein: origins, production and properties. *In Handbook of food proteins* (pp. 335-352). Woodhead Publishing.

Finnigan, T., Needham, L., & Abbott, C. (2017). Mycoprotein: a healthy new protein with a low environmental impact. *In Sustainable protein sources* (pp. 305-325). Academic Press.

García-Segovia, P., García Alcaraz, V., Tárrega, A., & Martínez-Monzó, J. (2020). Consumer perception and acceptability of microalgae based breadstick. *Food Science and Technology International, 26*(6), 493–502.

Gésan-Guiziou, G., Alaphilippe, A., Aubin, J., Bockstaller, C., Boutrou, R., Buche, P., ... & van der Werf, H. M. (2020). Diversity and potentiality of multi-criteria decision analysis methods for agri-food research. *Agronomy for Sustainable Development*, *40*, 1-11. https://doi.org/10.1007/s13593-020-00650-3

Grahl, S., Strack, M., Mensching, A., & Mörlein, D. (2020). Alternative protein sources in Western diets: Food product development and consumer acceptance of spirulina-filled pasta. *Food Quality and Preference*, 103933.

Grófová, Š, & Srnec, K. (2012). Food crisis, food production and poverty. *Agricultural Economics, 58*(3), 119–126.

Havemeier, S., Erickson, J., & Slavin, J. (2017). Dietary guidance for pulses: The challenge and opportunity to be part of both the vegetable and protein food groups. *Annals of the New York Academy of Sciences, 1392*(1), 58–66.

Hecht, A. A., Biehl, E., Barnett, D. J., & Neff, R. A. (2019). Urban food supply chain resilience for crises threatening food security: A qualitative study. *Journal of the academy of nutrition and dietetics, 119*(2), 211–224. https://doi.org/10.1016/j.jand.2018.09.001

Hellwig, C., Gmoser, R., Lundin, M., Taherzadeh, M. J., & Rousta, K. (2020). Fungi Burger from Stale Bread? A Case Study on Perceptions of a Novel Protein-Rich Food Product Made from an Edible Fungus. *Foods, 9*(8), 1112.

Hoefling, A., & Strack, F. (2010). Hunger induced changes in food choice. When beggars cannot be choosers even if they are allowed to choose. *Appetite*, *54*(3), 603-606.

Holliday, D. (2014). *Chemistry and Application of Pulses as Value-Added Ingredients in Processed Foods.* LSU Doctoral Dissertation. Retrieved from https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=2594&context=gradschool_dissertations

Hwang, J., & Choe, J. Y. (2020). How to enhance the image of edible insect restaurants: Focusing on perceived risk theory. *International Journal of Hospitality Management, 87*, 102464.

James, S. C., & Boriah, V. (2010). Modeling algae growth in an open-channel raceway. *Journal of Computational Biology, 17*(7), 895–906.

Kamau, E., Mutungi, C., Kinyuru, J., Imathiu, S., Tanga, C., Affognon, H., ... & Fiaboe, K. K. M. (2018). Moisture adsorption properties and shelf-life estimation of dried and pulverised edible house cricket Acheta domesticus (L.) and black soldier fly larvae Hermetia illucens (L.). *Food Research International*, *106*, 420-427.

Kovač, D. J., Simeunović, J. B., Babić, O. B., Mišan, A. Č, & Milovanović, I. L. (2013). Algae in food and feed. *Food and Feed Research, 40*(1), 21–32.

Koyande, A. K., Chew, K. W., Rambabu, K., Tao, Y., Chu, D. T., & Show, P. L. (2019). Microalgae: A potential alternative to health supplementation for humans. *Food Science and Human Wellness, 8*(1), 16–24.

Lane, H. W., Bourland, C., Barrett, A., Heer, M., & Smith, S. M. (2013). The role of nutritional research in the success of human space flight. *Advances in Nutrition, 4*(5), 521–523.

Luning, P. A. & Marcelis, W. J. (2011). Food Quality Management. Technological and managerial principles and practices. The Netherlands, Wageningen Academic Publishers.

Madau, F. A., Arru, B., Furesi, R., & Pulina, P. (2020). Insect Farming for Feed and Food Production from a Circular Business Model Perspective. *Sustainability, 12*(13), 5418.

Makkar, H. P., Tran, G., Heuzé, V., & Ankers, P. (2014). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology, 197*, 1–33.

Melendrez-Ruiz, J., Buatois, Q., Chambaron, S., Monnery-Patris, S., & Arvisenet, G. (2019). French consumers know the benefits of pulses, but do not choose them: An exploratory study combining indirect and direct approaches. *Appetite, 141*, 104311.

Melgar-Lalanne, G., Hernández-Álvarez, A. J., & Salinas-Castro, A. (2019). Edible insects processing: Traditional and innovative technologies. *Comprehensive Reviews in Food Science and Food Safety, 18*(4), 1166–1191.

Mishyna, M., Chen, J., & Benjamin, O. (2020). Sensory attributes of edible insects and insect-based foods–Future outlooks for enhancing consumer appeal. *Trends in Food Science & Technology, 95*, 141–148.

Modrak, V., Helo, P. T., & Matt, D. T. (2018). Complexity Measures and Models in Supply Chain Networks. *Complexity*, vol. 2018, Article ID 7015927.

Nosworthy, M. G., Neufeld, J., Frohlich, P., Young, G., Malcolmson, L., & House, J. D. (2017). Determination of the protein quality of cooked Canadian pulses. *Food Science & Nutrition, 5*(4), 896–903.

Özyurt, G., Uslu, L., Yuvka, I., Gökdoğan, S., Atci, G., Ak, B., & Işik, O. (2015). Evaluation of the cooking quality characteristics of pasta enriched with Spirulina platensis. *Journal of Food Quality, 38*(4), 268–272.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., ... & Alewell, C. (2015). Rainfall erosivity in Europe. *Science of the Total Environment*, *511*, 801-814.

Perchonok, M., & Bourland, C. (2002). NASA food systems: past, present, and future. *Nutrition, 18*(10), 913–920.

Pojić, M., Mišan, A., & Tiwari, B. (2018). Eco-innovative technologies for extraction of proteins for human consumption from renewable protein sources of plant origin. *Trends in Food Science & Technology, 75*, 93–104.

Post, M. J., & Hocquette, J. F. (2017). New sources of animal proteins: cultured meat. *In New Aspects of Meat Quality* (pp. 425-441). Woodhead Publishing.

Putt, R., Singh, M., Chinnasamy, S., & Das, K. C. (2011). An efficient system for carbonation of high-rate algae pond water to enhance CO2 mass transfer. *Bioresource Technology, 102*(3), 3240–3245.

Ravzanaadii, N., Kim, S. H., Choi, W. H., Hong, S. J., & Kim, N. J. (2012). Nutritional value of mealworm, Tenebrio molitor as food source. *International Journal of Industrial Entomology, 25*(1), 93–98.

RIVM. (2016). *National Risk Profile 2016. An All Hazard overview of potential disasters and threats in the Netherlands. The National Network of Safety and Security Analysts*. National Institute for Public Health and the Environment. Retrieved from https://www.clingendael.org/sites/default/files/2017-09/Dutch%20National%20Risk%20Profile%202016_english.pdf

Sakar, A., Hongyu, W., Jony, A.A., Das, J.C., Memon, W.H. & Qian, L. (2021). Evaluation of the determinants of food security within the COVI-19 pandemic circumstances – a particular case of Shaanxi, China. *Global Health Research and Policy*, https://doi.org/10.1186/s41256-021-00230-2.

Salami, S. A., Luciano, G., O'Grady, M. N., Biondi, L., Newbold, C. J., Kerry, J. P., & Priolo, A. (2019). Sustainability of feeding plant by-products: A review of the implications for ruminant meat production. *Animal Feed Science and Technology, 251*, 37–55.

Savary, S., Akter, S., Almekinders, C., Harris, J., Korsten, L., Rötter, R. Waddington, S. & Watson, D. (2020). Mapping disruption and resilience mechanisms in food systems. *Food Security (12)*, 695-717.

Schaafsma, G. (2005). The Protein Digestibility-Corrected Amino Acid Score (PDCAAS)-a concept for describing protein quality in foods and food ingredients: a critical review. *The Journal of AOAC International, 88*(3), 988–994.

Schwartz, N., Buliung, R., & Wilson, K. (2019). Disability and food access and insecurity: A scoping review of the literature. *Health & place, 57*, 107–121.

Schneider, A. V. (2002). Overview of the market and consumption of puises in Europe. *British Journal of Nutrition, 88*(S3), 243–250.

Sharoba, A. M. (2014). Nutritional value of spirulina and its use in the preparation of some complementary baby food formulas. *Journal of Food and Dairy Sciences, 5*(8), 517–538.

Singh, R. P. (2013). Status paper on pulses. Government of India, Ministry of Agriculture, Directorate of Pulses Development. Retrieved from https://www.farmer.gov.in/imagedefault/pestanddiseasescrops/pulses.pdf

Smetana, S., Mathys, A., Knoch, A., & Heinz, V. (2015). Meat alternatives: life cycle assessment of most known meat substitutes. *The International Journal of Life Cycle Assessment, 20*(9), 1254–1267.

Smith, S. M. (2009). Nutritional Biochemistry of Space Flight (Space Science, Exploration and Policies Series). Nova Science Publishers Incorporated.

Sokhansanj, S. H. A. H. A. B., & Patil, R. T. (2003). Dehulling and splitting pulses. *Handbook of postharvest technology: cereals, fruits, vegetables, tea, and spices, 93*, 397.

Souza Filho, P. F., Andersson, D., Ferreira, J. A., & Taherzadeh, M. J. (2019). Mycoprotein: environmental impact and health aspects. *World Journal of Microbiology and Biotechnology, 35*(10), 147.

Stringer, L. C., Fraser, E. D., Harris, D., Lyon, C., Pereira, L., Ward, C. F., & Simelton, E. (2020). Adaptation and development pathways for different types of farmers. *Environmental Science & Policy, 104*, 174–189.

Tang, G., & Suter, P. M. (2011). Vitamin A, nutrition, and health values of algae: Spirulina, Chlorella, and Dunaliella. *Journal of Pharmacy and Nutrition Sciences, 1*(2), 111–118.

Terluin, I. J., Kamphuis, B. M., Oudendag, D. A., & van Leeuwen, M. G. (2013). *Voedselvoorziening in Nederland onder buitengewone crisisomstandigheden*. LEI, onderdeel van Wageningen UR.

Tiburcio, P. C., Galvez, F. C. F., Cruz, L. J., & Gavino, V. C. (2007). Determination of shelf life of Spirulina platensis (MI 2) grown in the Philippines. *Journal of applied phycology, 19*(6), 727–731.

Toffolutti, V., Stuckler, D., & McKee, M. (2020). Is the COVID-19 pandemic turning into a European food crisis? *European journal of public health, 30*(4), 626–627.

Trinci, A. P. (1992). Myco-protein: A twenty-year overnight success story. *Mycological Research, 96*(1), 1–13.

Tuomisto, H. L. (2010). Food security and protein supply: cultured meat a solution. *Asp. Appl. Biol, 102*, 99–104.

Tuomisto, H. L., & Teixeira de Mattos, M. J. (2011). Environmental impacts of cultured meat production. *Environmental science & technology, 45*(14), 6117–6123.

Tuomisto, H. L., Ellis, M. J., & Haastrup, P. (2014, October). Environmental impacts of cultured meat: alternative production scenarios. *In 9th International Conference on Life Cycle Assessment in the Agri-Food Sector*.

Turk, D., Castenmiller, J., De Henauw, S., Hirsch-Ernst, K. I., Kearney, J., Maciuk, A., … & Knutsen, H. K. (2021). Safety of dried yellow mealworm (Tenebrio molitor larva) as a novel food pursuant to Regulation (EU) 2015/2283. EFSA: Scientific Opinion. *EFSA Journal, 19*(1), 6343. Retrieved from https://www.efsa.europa.eu/sites/default/files/scientific_output/6343.pdf

Tyner, K. (2020). *The Future of Animal-Free Meat*. Magnificat. Retrieved from: https://commons.marymount.edu/magnificat/the-future-of-animal-free-meat/

USDA (2023). *FoodData Central*. U.S. Department of Agriculture. Retrieved from: https://fdc.nal.usda.gov/ndb/search/list?qlookup=manu=SYNCHRONIZER_TOKEN=20e375c9-6d38-4b4b-af97-72f695e33273SYNCHRONIZER_URI=%2Fndb%2Fsearch%2Flistds

Van der Weele, C., & Tramper, J. (2014). Cultured meat: every village its own factory? *Trends in biotechnology, 32*(6), 294–296.

Van der Weele, C., Feindt, P., van der Goot, A. J., van Mierlo, B., & van Boekel, M. (2019). Meat alternatives: an integrative comparison. *Trends in Food Science & Technology, 88*, 505–512.

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects: future prospects for food and feed security* (No. 171). Food and Agriculture Organization of the United Nations.

Van Huis, A. (2016). Edible insects are the future? *Proceedings of the Nutrition Society, 75*(3), 294–305.

Van Krimpen, M. M., Bikker, P., Van der Meer, I. M., Van der Peet-Schwering, C. M. C., & Vereijken, J. M. (2013). *Cultivation, processing and nutritional aspects for pigs and poultry of European protein sources as alternatives for imported soybean products* (No. 662). Wageningen UR Livestock Research.

Van Wassenhove, L. N. (2006). Humanitarian aid logistics: supply chain management in high gear. *Journal of the Operational Research Society, 57*(5), 475–489.

Vigani, M., Parisi, C., Rodríguez-Cerezo, E., Barbosa, M. J., Sijtsma, L., Ploeg, M., & Enzing, C. (2015). Food and feed products from micro-algae: Market opportunities and challenges for the EU. *Trends in Food Science & Technology, 42*(1), 81–92.

Voloshin, R. A., Rodionova, M. V., Zharmukhamedov, S. K., Veziroglu, T. N., & Allakhverdiev, S. I. (2016). Biofuel production from plant and algal biomass. *International journal of hydrogen energy, 41*(39), 17257–17273.

Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., ... & Brawley, S. H. (2017). Algae as nutritional and functional food sources: revisiting our understanding. *Journal of applied phycology, 29*(2), 949-982.

WFP. (2023). *A global food crisis*. World Food Program. Retrieved from https://www.wfp.org/global-hunger-crisis

Wiebe, M. (2002). Myco-protein from Fusarium venenatum: a well-established product for human consumption. *Applied Microbiology and Biotechnology, 58*(4), 421–427.

Wu, G., Wu, Z., Dai, Z., Yang, Y., Wang, W., Liu, C., ... & Yin, Y. (2013). Dietary requirements of "nutritionally non-essential amino acids" by animals and humans. *Amino acids, 44*(4), 1107-1113.

Wurgaft, B. A. (2020). Meat Mimesis: Laboratory-Grown Meat as a Study in Copying. *Osiris, 35*(1), 310–323.

Xipsiti, M., Marzara, S., & Calles, T. (2017). International Year of Pulses: Keeping the momentum beyond 2016. *Nutrition Bulletin, 42*(4), 346–350.

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