COVID-19 demand-induced scarcity effects on nutrition and environment: investigating mitigation strategies for eggs and wheat flour in the United Kingdom

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Abstract

The COVID-19 pandemic has drawn attention to food insecurity in developed countries. Despite adequate levels of agricultural production, consumers experienced demand-induced scarcity. Understanding the effects on nutrition and the environment is limited, yet critical to informing ecologically embedded mitigation strategies. To identify mitigation strategies, we investigated wheat flour and egg retail shortages in the United Kingdom (UK), focusing on consumer behavior during the COVID-19 lockdown. The 6 Steps for Quality Intervention Development (6SQuID) framework informed the methodology. Mixed qualitative and quantitative methods were used to pinpoint the causes of the shortages, and ecological impacts of consumer behavior were related using survey results (n = 243) and environmental and nutritional databases. This research confirmed consumers' narrowed consideration set, willingness to pay, and significant reliance on processed foods which indicates agronomic biofortification, breeding strategies, selective imports and improved processed food quality are important mitigation strategies. We identified positive and negative synergies in consumer, producer and retailer behavior and related these to mitigation strategies in support of a circular bio-economy for food production. We found that the substitutes or alternative foods consumed during the COVID-19 lockdown were nutritionally inadequate. We identified the most ecological substitute for wheat flour to be corn flour; and for eggs, yogurt. Our findings also indicate that selenium deficiency is a risk for the UK population, especially to the increasing fifth of the population that is vegetarian. Due to the need to implement short-, medium-, and long-term mitigation strategies, a coordinated effort is required by all stakeholders.

Keywords: circular economy, coronavirus, ecological embeddedness, food security, food waste, public health nutrition

1. Introduction

The World Bank raised concerns about a potential rise in food insecurity during the COVID-19 pandemic (The World Bank, 2020a). Although support schemes are currently in place, there may be a significant reduction in the ability of newly unemployed people to purchase food when these schemes end. There may also be a challenge to maintain agricultural production to supply affordable and nutritious food to consumers affected by movement restrictions and/or reduced incomes. It is, therefore, important to understand how detrimental environmental and nutritional impacts may be alleviated.

Although global production levels for rice, wheat and corn are not currently a concern (The World Bank, 2020b), this has not stopped consumers from experiencing demand-induced scarcity during COVID-19 lockdowns in developed countries due to domestic food supply chains and other shocks. Looking ahead, similar disruptions are likely to be the new norm with climate change bringing uncharted droughts and floods as well as temperature changes affecting agricultural production and increased risk of disease. The COVID-19 crisis is seen as deeply connected with the crises of climate and biodiversity (Armstrong et al., 2020).

England has been effectively famine-free since the eve of the Industrial Revolution (Campbell & Gráda, 2011). However, there are ongoing reminders of the fragility of the food system related to political causes: protests over fuel prices in 2000 which led to rationing in supermarkets and some shops being bare of bread and milk; stockpiling by consumers and food industry over Brexit-related food supply concerns in 2018; and climate related events such as the vegetable shortages due to bad weather in Spain and Italy in 2017. At times of food scarcity, it is particularly important to improve food sustainability and reduce food waste. There is a lack of knowledge about mitigation strategies to ensure that the general population is able to access a nutritious diet without resorting to unsustainable behavior. The concept is based on ecological embeddedness which seeks benefits to both the economic actors (consumers and producers) and the natural environment (Trollman & Colwill, 2020). This research makes a case for systems-level understanding of consumer behavior when faced with scarcity or shortages, particularly in countries where this has not been a common recent experience and affluence is correlated with increased food waste (van den Bos Verma et al., 2020). The reason that consumer behavior is studied is because product scarcity affects consumer behavior (Oruc, 2015).

This research employs a survey to investigate consumer behavior and related effects on food waste and nutrition with respect to egg and wheat flour demand-induced scarcity during the COVID-19 lockdown in the United Kingdom (UK) to inform policy and suggest mitigation strategies. The survey was combined with preliminary life cycle assessment (LCA) to contribute to the evaluation of the environmental impact of consumer choices of substitutes for eggs and wheat flour with the motivation of identifying those with the least potential environmental impact. Wheat flour and eggs are an important part of the diet in the UK with 59 kg of wheat flour consumed per person per year in 2018/19 (nabim, 2019a) and 197 eggs consumed per person in 2019 (egg info, 2020). Consequently, shortages of these two food items have the potential to significantly affect diets, which motivated their selection for this study.

The objective of this paper is to utilize the theory of ecological embeddedness (Morris & Kirwan, 2011; Trollman et al., 2020; Trollman & Colwill, 2020) to identify mitigating strategies for the demand-induced scarcity of wheat flour and eggs during COVID-19 in the UK. Initially, it will be confirmed that the scarcity of wheat flour and eggs was demand-induced. This is followed by a description of the food waste, nutrition, consumer behavior nexus.

2. Literature Review

In this section, we review the most relevant and recent research related to the interconnection of food security and nutrition, and consumer behavior in times of scarcity.

2.1 Food Security and Nutrition

Previous research on food sustainability has examined the importance consumers attach to critical sustainable attributes of food related to food waste by examining agricultural products such as potatoes (visual imperfections, washed/unwashed, size, locally produced and price) (Jagtap & Rahimifard, 2019; Gracia & Gómez, 2020). These studies focus on heterogeneous consumer behavior not affected by scarcity or shortages. Social and economic aspects of sustainability are often not included in food systems modeling (Auestad & Fulgoni 3rd, 2015). This is a significant oversight as research has found that the strongest positive correlation with food system sustainability was economic (Bene et al., 2020).

There has been very little research connecting food security with nutrition which are often addressed separately in the literature (El Bilali et al., 2019). Consensus recommendations suggest reframing the current focus on sustainable diets towards achieving healthy dietary patterns from sustainable food systems (Comerford et al., 2020). Research suggests a participatory approach to sustainable nutrient management (Nanda et al., 2020) and an interdisciplinary whole of food systems approach for public health nutrition (Waterlander et al., 2018).

The Coping Strategies Index (CSI) is one example of an assessment designed to investigate how households cope with food shortfalls (Maxwell et al., 2003). When CSI scores are calculated for other households in the same community or region, a comparative indicator of household food security is obtained. The related four main categories of coping behaviors are dietary change, short-term unsustainable measures to increase household food availability, rationing strategies and reduction in the number of people provided for (Maxwell et al., 2008).

Anthropometry is the domain of food security that is used as a proxy to measure food utilization. It encompasses the allocation of food within households, the nutritional quality of that food and the bioavailability of nutrients in those foods. However, food utilization estimates that rely on anthropometric measurements alone may misrepresent inadequate nutritional intake (Jones et al., 2013).

Acquiring food in socially unacceptable ways (e.g., asking others for food, shoplifting) is another aspect of food access, but it is generally absent from metrics and surveys due to the sensitive nature of the topic and difficulty obtaining accurate responses. Similarly, the safety of foods acquired by households is often absent from food security metrics (Jones et al., 2013).

Evidence indicates that sustainable diets and food systems are interdependent, dynamic and significantly influenced by geography and regional or local economic conditions. A transdisciplinary approach is recommended to inform practical frameworks and models, relevant trade-offs, synergies, and unintended consequences (Comerford et al., 2020). Three primary actions are often considered to achieve sustainability benefits: (i) changes towards healthier diets, (ii) production and transport innovations, and (iii) reductions in food loss and waste (FAO, 2019). The important contribution of this work is to assess the interactions of food scarcity with the environment and nutrition by employing a survey to gather data that is generally absent from the literature.

2.2 Consumer Behavior

The psychology of scarcity suggests that consumers will make decisions to advance their own welfare, and that these may manifest as either selfish or generous behaviors for personal gains (Roux et al., 2015). Grossman and Mendoza (2003) hypothesize that as a resource (e.g., food) becomes scarce, people will expend more time and effort competing with others for that resource. Product shortages have led to violent competitive reactions among consumers in the past, and most consumers are familiar with resource scarcity engendering this type of competitive response. There is evidence for a positive relationship between scarcity and antisocial behavior (Prediger et al., 2014; Kristofferson et al., 2017). With respect to food, previous research finds that scarce foods are perceived as having more calories because scarce food is seen as more valuable and expensive, leading to motivated perception in which higher calorie estimates are the result of a desire to acquire more of the scarce product (Salerno & Sevilla, 2019).

At the time of this study, resource scarcity, defined as the real or perceived lack of various forms of capital (i.e., financial, social, cultural) or other production inputs (i.e., time) that consumers invest to acquire food products, was not massively impacted due to furlough and similar government support schemes to tackle the spread of COVID-19. This is to distinguish access to products (ends) from access to resources (means). However, product scarcity, the real or perceived lack of food products, was an issue during the lockdown period of COVID-19 in the UK. Both variety scarcity, meaning that there was a limited available quantity of a specific brand or amount, and category scarcity, a lack of access to an entire food product category, were present.

Research suggests that if a product is restricted in supply, consumers may be willing to pay more for it (Roy & Sharma, 2015). Scarcity induces polarized judgments which may have adverse consequences for food consumption as consumers may not benefit from more varied consumption (Hamilton et al., 2019). If a product is not available (an extreme form of product scarcity), consumers may either defer consumption or select a substitute (Hamilton et al., 2014). Variety scarcity (e.g., a specific brand is not available) may lead to the purchase of an alternative within that product category, but category scarcity (the product is not available) means the purchase must be postponed or a substitute from a different product category is selected. In the special case of eggs and wheat flour examined in this research, substitutes may be sought that fulfill the same role from a similar or dissimilar product category.

Consumers tend to select substitutes that are perceived as being similar to their initial choice with more dissimilar alternatives, often reducing the desire for the product that was originally sought (Arens & Hamilton, 2016, 2018). Overconsumption may occur if the substitute does not reduce desire for the original product as both may be consumed. Product scarcity tends to narrow consideration sets (Zhu & Ratner, 2015), whereas resource scarcity tends to broaden consideration sets including creative substitutes (Hill et al., 1998). There may be long-term effects on consumer habits, behavior and brand loyalty as a result of substitutions due to scarcity. Substitution in both consumption and production processes is prompted by scarcity (Hamilton, 2020).

One of the few studies of consumer behavior in the presence of scarcity is of the economic crisis in Poland (1980s) (Gajewski, 1992), which indicates that forced expenditure, consumption renaturalization, coping with relatively low quality of production and the black/grey market are part of consumer attempts to satisfy needs. The Polish situation differs from the current COVID-19 lockdown as Poland could be characterized as not only experiencing economics of shortage, but also protracted and deep economic, social and political crisis consisting of considerable shortages in the supply of consumer goods, high rates of inflation, different forms of rationing and a drop in real incomes. It remains to be seen if such conditions materialize as a result of the COVID-19 pandemic, however, the presence of these behaviors is also investigated in this research.

Table 1 summarizes the previous research which informed the survey. Table 1 represents a priori theorizing as part of the formulation of explicit hypotheses about the reactions of consumers to demand-induced scarcity based on related literature (Reiter, 2017). Related literature is used as no directly applicable literature was identified due to the concept of ecological embeddedness not being previously explored in the context of demand-induced scarcity.

Table 1. Research questions and their sources.

Research Question	Research Aspects	Source
What substitutes were used?	-coping behavior: dietary change	(Maxwell et al., 2008)
	-deferred consumption	(Hamilton et al., 2014)
	-environmental impact (trade-offs, synergies, and unintended consequences)	(Comerford et al., 2020)
	-narrowed consideration set	(Zhu & Ratner, 2015)
	-reductions in food loss and waste	(FAO, 2019)
	-relative nutritional value of substitute -similar or dissimilar substitute	(Arens & Hamilton, 2016; Arens & Hamilton, 2018)
	-varied consumption	(Hamilton et al., 2019)
What alternative was consumed?	-coping behavior: dietary change	(Maxwell et al., 2008)
	-deferred consumption	(Hamilton et al., 2014)
	-environmental impact (trade-offs, synergies, and unintended consequences)	(Comerford et al., 2020; FAO, 2019)
	-narrowed consideration set	(Zhu & Ratner, 2015)
	-reductions in food loss and waste	(FAO, 2019)
	-relative nutritional value of substitute -similar or dissimilar substitute	(Arens & Hamilton, 2016; Arens & Hamilton, 2018)
	-varied consumption	(Hamilton et al., 2019)
Were new recipes used with substitutes for the products sought? Were failed recipes attempted again with a different substitute? Were successful recipes made again?	-food waste	(FAO, 2019)
	-increased time and effort (repeated)	(Grossman & Mendoze, 2003)
Were products purchased if the price was more than before the COVID-19 lockdown?	-value associated with scarce resource	(Mullainathan & Shafir, 2013; Spiller, 2011)
	-willingness to pay	(Roy & Sharma, 2015)
Was quality equivalent to before the COVID-19 lockdown?	-relatively low quality of production	(Gajewski, 1992)

Was an equivalent processed food product purchased to what would have been made?	-diminished processed food role / consumption renaturalization	(Gajewski, 1992)
If the product was found but not needed, was it purchased? Was an unrelated food product purchased instead?	-coping behavior: dietary change -short-term unsustainable measures to increase household food availability	(Maxwell et al., 2008)
	-environmental impact (trade-offs, synergies, and unintended consequences)	(Comerford et al., 2020; FAO, 2019)
	-forced expenditure	(Gajewski, 1992)
	-relative nutritional value of substitute -similar or dissimilar substitute	(Arens & Hamilton, 2016; Arens & Hamilton, 2018)
	-selfish behavior	(Roux et al., 2015)
Were products sought on the black/grey market?	-acquiring food in socially unacceptable ways	(Jones et al., 2013)
	-presence of a black/grey market	(Gajewski, 1992)

To date, there has been relatively limited research on the topic of scarcity, and it is not known if existing research can be generalized (Hamilton et al., 2019). This work contributes to the knowledge of product scarcity in the most extreme case (product not available) and furthers knowledge of consumer response in the real-world. Much of the existing work on resource scarcity in the fields of psychology and marketing has been on populations that may have limited resources by Western standards or homogeneous levels of resources (e.g., college students). Studying consumers with a wide range of resources is a challenge as it is difficult to gain access to consumers who have experienced severe resource scarcity. As reminders of scarcity do exist, consumers often think about, worry about and discuss scarcity-related concerns (Twist & Barker, 2006). However, the COVID-19 pandemic has provided a unique opportunity to examine the actual effect. The research gap that is addressed by this work is that demand-induced food scarcity in a developed country has not been fully investigated in the literature to identify the impact consumer behavior has on food waste and nutrition. This research gap is used to answer the research question 'What ecologically embedded mitigation strategies may be employed to address demand-induced scarcity?'

2.3 COVID-19 Research

This section presents a brief review of relevant literature available on Scopus to 11 February 2021.

The issue of food waste during COVID-19 has been examined by researchers with mixed findings. Some studies suggest that the pandemic has improved the awareness of food waste e.g., (Jribi et al., 2020; Rejeb et al., 2020) and in some cases reduced its generation e.g., (Rodgers et al., 2021; Pappalardo et al., 2020; Qian et al., 2020) although with larger intermittent pandemic-driven purges of food (Roe et al., 2020). The need for consumer education has been highlighted (Cosgrove et al., 2021). Other studies cite food waste increase during the pandemic (Zhao & You, 2021; Brizi & Biraglia, 2021) together with decrease in nutritional content of the food consumed (Aldaco et al., 2020). A cross-continental comparison of consumer behavior during the initial COVID-19 phase found an increase in saturated fat intake (Murphy et al., 2020). Others claim a shift to healthier, more sustainable food (Borsellino et al., 2020; Hassen et al., 2020). Selenium status and other micronutrients have been reported to have a positive effect on COVID-19 outcomes e.g., (Majeed et al., 2021; Gorji et al., 2021; Heller et al., 2021).

COVID-19 has been found to have an important effect on agriculture and the food supply chain mainly through food demand and consequent food security (Siche, 2020). Food retailers and their supply chains were unprepared for panic buying during the initial stages of the COVID-19 pandemic (Barnes et al., 2021). Food waste has been related to consumer behavior through hoarding / stockpiling food / panic buying. A study of stockpiling behavior in China indicates that consumers are, on average, willing to pay a premium for fresh products reserves (Wang et al., 2020). A descriptive analysis of the COVID-19 impacts on U.S. pork, turkey and egg markets highlights some opportunities for resiliency strategies (Hayes et al., 2020). There are calls in the literature for transformative change to supply chains (Mollenkopf et al., 2020) and redefining the concept of sustainability (Hakovirta & Denuwara, 2020). Social responsibility of manufacturers is recognized as part of the response, and strategies for mitigation of high-demand essential non-food items during a pandemic situation have been proposed (Paul & Chowdhury, 2020). This research offers unique insight into the transformation of food supply chains for ecological embeddedness through the consideration of both food waste management, environmental impact and public health nutrition in light of COVID-19 to inform response to similar shocks in the future.

3. Research Methodology

This study employs an exploratory research design which is appropriate for problems on which little or no previous research has been done to find a range of possible solutions to a specific problem. Exploratory design calls for either unstructured or semi-structured data collection methods. For this reason, the questionnaire has both closed and open questions and additional data was collected based on the results of the questionnaire. Likewise, exploratory research requires fluid and flexible data analysis. For this reason, both quantitative and qualitative analysis are employed.

The research methodology employed considered the WHO guidelines (World Health Organization, 2020) to ensure this research did not impede emergency response efforts, was based on both international and local priorities, and involved fair and meaningful community engagement for scientific validity and social value.

The mitigation strategies sought are public health interventions combined with environmental considerations, so a modified 6 Steps for Quality Intervention Development (6SQuID) framework informed the methodology employing four of the six steps (Wight et al., 2016) as described in Table 2.

Table 2. Methodology: 6 Steps for Quality Intervention Development (6SQuID)

6 Steps in Quality Intervention Development (6SQuiD)	Application of 6SQuID to the research context	Method(s) used in the research

Step 1. Define and understand the problem and causes	Problem: Scarcity of eggs and wheat flour in retail during the first lockdown of COVID-19 in the UK. Causes: Demand-induced scarcity. Consequences: nutritional insufficiency, food waste, behavioral change.	Observation, literature review, survey.
Step 2. Identify modifiable causal or contextual factors with greatest scope for change and who would benefit most.	Causal factors: supply chain (farm to fork), consumer behavior. Contextual factors: food production, retailer reaction, food waste management, healthcare system. Beneficiaries: Economic actors, natural environment.	Qualitative analysis of consumer food choices (nutritional value) and food waste treatment options. Quantitative analysis of consumer behavior and food waste generated (descriptive and inferential statistics from survey). Preliminary Life-Cycle Assessment (LCA).
Step 3. Decide on the mechanisms of change.	Mechanisms identified throughout the value chain.	Systems thinking: conceptual model of value chain. Data analysis: short-, medium- and long-term classification of changes.
Step 4. Clarify delivery.	Identification of positive and negative synergies between demand-induced scarcity and consumer, producer and retailer behavior.	Data and gap analysis for mitigation strategies: observed during COVID-19, theoretical, or proposed.
Step 5. Test and adapt the intervention.	Future work.	Not applicable.
Step 6. Collect sufficient evidence of effectiveness for rigorous evaluation.	Future work.	Not applicable.

For a holistic examination of the scarcity of eggs and wheat flour in the UK during the COVID-19 lockdown, it was first important to understand the causes to confirm that the scarcity was demand-induced. For this reason, an investigation of the supply chains was undertaken. This included UK production, import, distribution, household consumption, food manufacturer consumption, and capacity issues. For egg supply chains, additionally raw materials and supplies for poultry production.

This was followed by the development of a survey based on literature to investigate consumer behavior in relation to the demand-induced scarcity. The full questionnaire is in the Supplementary Information. The research aspects in Table 1 determined which information would be sought from respondents. The investigation of the presence of behaviors noted in the research supported external validity. An opening question was included so that only those respondents who experienced egg or wheat flour scarcity in the UK would continue to the other questions. The question content was selected to minimize confusion. An opportunity was provided for an open-ended response in addition to the 'yes/no' format. The open-ended confirmation of respondents supported reliability of the questionnaire. The questions were put into a meaningful order to minimize bias, encourage completion of the survey, and grouped by aspect. The most uncomfortable question about black/grey market was hence the last question.

The questionnaire was piloted on 10 volunteers and revised prior to release. Revision of the questionnaire benefited from experience in food industry, particularly for the question about quality, which may mean significantly different things to different people. Consequently, this question was annotated for respondents to include product, packaging, and quantity. Relevant questions included examples of responses to inform respondents.

The survey examined consumer behavior in response to wheat flour and egg scarcity during the COVID-19 lockdown in the UK (March – June 2020), paying specific attention to impacts on food waste and nutrition. The UK was targeted as media reports indicated there was widespread lack of availability of wheat flour and eggs during the COVID-19 lockdown. The evaluation aimed to identify detrimental impacts and potential mitigation strategies.

The questionnaire was shared via social media, university mailing lists and a press release. The questionnaire was anonymous to improve the likelihood of obtaining accurate responses due to the sensitive nature of some of the questions related to socially unacceptable behavior. A total of 243 responses were obtained from 18 May 2020 to 9 July 2020. Data collection was ended as some responses to the survey indicated that respondents were beginning to forget what their actions had been.

This research was intended to capture a heterogenous response from the population. People without access to the internet would, however, be excluded as the questionnaire was only disseminated online. This would exclude about 7% of households as the share of households that have internet access in the UK in 2019 is estimated to be 93% (Office for National Statistics, 2019a).

Data were initially analyzed using statistical methods: descriptive statistics and inferential statistics. The descriptive statistics were sample size, number of responses per question (percentage), and number of responses per question as a percentage of the sample. The inferential statistics were margin of error and confidence interval for the sample. This was followed by a qualitative analysis of the food choices of consumers.

The impact of food waste was assessed using the Food Waste Management Decision Tree (FWMDT) (Garcia-Garcia et al., 2017). The amount of food waste was estimated by extrapolating the responses to the food waste questions to the general population and assuming the same amount of ingredient would be needed for the substitute as for the original ingredient (57 g of ingredient for egg substitutes and 120 g for wheat flour substitutes).

Preliminary Life-Cycle Assessment (LCA) was used to compare the environmental impact of eggs and wheat flour production with the substitutes used by respondents to the survey. LCA is a widely-used methodology to assess the environmental impact of products over their life cycle. The environmental data for the life-cycle inventory were collected from the commercial databases listed in Table 3. Cut-off processes, to allocate all the environmental impact to the main product to be commercialized, were prioritized. In terms of the geographical scope, global and European were selected, as the conclusions from the environmental impact study could be applicable to any country. The impact assessment method used was IPCC 2013 GWP 100a V1.03, widely used to assess the global warming potential of processes and products.

Table 3. Products and databases used to represent eggs, wheat flour and their substitutes

Ingredient	**Product in database**	**Database**
Eggs	Consumption eggs, laying hens >17 weeks, at farm/NL Economic	Agri-footprint
Baking soda	Sodium bicarbonate {RER}| soda production, solvay process | Cut-off, S	Ecoinvent 3
Potato starch	Potato starch {GLO}| market for | Cut-off, S	Ecoinvent 3
Oil	Refined sunflower oil, from crushing (pressing) at plant/UA Economic	Agri-footprint
Yogurt	Yogurt, from cow milk {GLO}| market for | Cut-off, S	Ecoinvent 3
Wheat flour	Wheat flour, from dry milling, at plant/UK Economic	Agri-footprint
Oat flour	Oat grain {GLO}| market for | Cut-off, S	Ecoinvent 3
Rice flour	Rice {GLO}| market for | Cut-off, S	Ecoinvent 3
Coconut	Coconut, dehusked {GLO}| market for coconut, dehusked | Cut-off, S	Ecoinvent 3
Corn flour	Sweet corn {GLO}| market for sweet corn | Cut-off, S	Ecoinvent 3
Tapioca flour	Tapioca starch, from processing without use of co-products, at plant/TH Economic	Agri-footprint

Again, we assumed that the same amount of ingredient would be needed for the substitute as for the original ingredient. This meant that the functional unit chosen was the production of 57 g of ingredient for the egg and egg substitutes, and 120 g for the wheat flour and its substitutes. This is unrealistic in the case of potato starch or baking soda as a recommended egg substitute is 7 g of baking soda combined with 15 g of vinegar, but reasonable for oil and yogurt (60 g of plain yogurt or buttermilk is a good substitute for an egg (McDonell, 2017)). Even so, as the environmental impacts of baking soda and potato starch are comparatively much lower than the other substitutes investigated, the conclusions are not affected. The environmental impact data for the different ingredients investigated based on responses to the survey are shown in Figure 1.

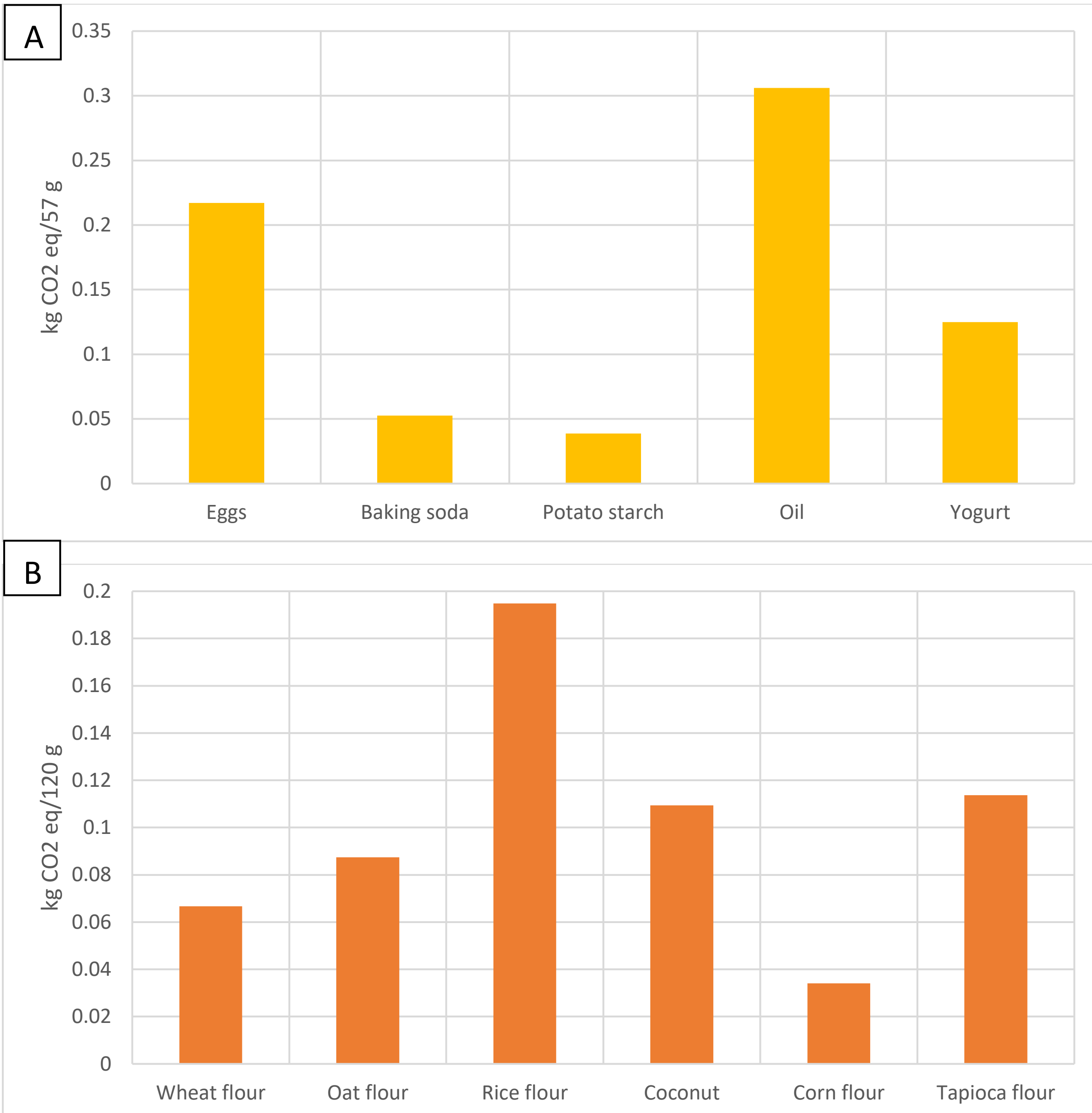

Figure 1. Global warming potential of A) egg and their substitutes, and B) wheat flour and their substitutes

To investigate the nutritional impact of respondents' alternative food choices, percentage of Daily Value (DV) for a diet of 2,000 calories a day for wheat flour and egg were compared with substitutes used by respondents. This comparison was used to indicate the main contributions of wheat flour and egg to the diet and how this contribution may change when a substitute is used.

The analysis of nutritional information relied on three databases: (Nutrition value, 2020) which uses data from the USDA National Nutrient Database for Standard Reference to identify percentage daily values (DV) of nutrients based on a diet of 2,000 calories a day; European Food Safety Authority Dietary reference values for nutrients (European Food Safety Authority (EFSA), 2019 update); and Food composition data (European Food Safety Authority (EFSA), 2020). The reason for using these three databases is that the USDA information is more comprehensive. In contrast, the European Food composition data only looks at 16 components but provides data specific to the UK. Additional information was obtained from relevant literature. The nutritional information relied on is presented in Tables 4 and 5.

The nutritional information was also used to identify potential nutrient deficiencies due to not having wheat flour or eggs in the diet. The results were checked with relevant literature. This was done by comparison of nutritional information for wheat flour and eggs with the substitutes used by respondents to the survey in order to assess the extent to which the substitutes could make up for the potential nutritional deficiencies.

Table 4. Wheat flour and substitutes calorific and nutritional value comparison. Minerals and proteins / amino acids are only listed for the reference base > 20% DV in wheat flour (italics). Source https://www.nutritionvalue.org/. DV = % Daily Value for a diet of 2,000 calories a day.

Ingredient	**Calories per 100g**	**Total Carbohydrate**	**Dietary Fiber**	**Protein**	**Fat**	**Minerals: Selenium/Manganese**	**Proteins and Amino acids: Isoleucine/Leucine/Phenylalanine/Threonine/Tryptophan/Valine**
Wheat flour, unenriched, all-purpose, white	*364 kcal*	*28% (76g)*	*10% (2.7g)*	*21% (10.33g)*	*1% (0.98 g)*	*62% (33.9 mcg)/ 30% (0.682 mg)*	*26%(0.357g)/26%(0.710g/30%(0.520g)/27%(0.281g)/45%(0.127g)/23%(0.415g)*
Buckwheat flour, whole groat	335 kcal	26% (71g)	36% (10g)	26% (13g)	4% (3.1g)	10% (5.7 mcg) / 88% (2.03 mg)	34%(0.474g)/29%(0.792g)/28%(0.495g)/46%(0.482g)/65%(0.183g)/35%(0.646g)
Chick pea flour/gram flour (besan)	387 kcal	21% (58g)	39% (11g)	44% (22g)	9% (6.7g)	15% (8.3 mcg)/ 70% (1.6 mg)	63%(0.882g)/54%(1.465g)/63%(1.103g)/73%(0.766g)/71%(0.2g)/48%(0.865g)(based on raw mature seeds)
Coconut meat, raw	354 kcal	5% (15g)	32% (9g)	7% (3.3g)	42% (33g)	18% (10.1 mcg)/ 65% (1.5 mg)	9%(0.131g)/9%(0.247g)/10%(0.169g)/12%(0.121g)/14%(0.039g)/11%(0.202g)
Corn flour, white, wholegrain	361 kcal	28% (77g)	26% (7.3g)	14% (6.9g)	5% (3.9g)	28% (15.4 mcg) / 20% (0.460 mg)	18%(0.248g)/31%(0.850g)/19%(0.340g)/25%(0.261g)/18%(0.049g)/19%(0.351g)
Flax seeds	534 kcal	11% (29g)	96% (27g)	36% (18g)	54% (42g)	46% (25.4 mcg) / 108% (2.482 mg)	64%(0.896g)/45%(1.235g)/55%(0.957g)/73%(0.766g)/106%(0.297g)/59%(1.072g)
Polenta (cornmeal, white, whole-grain)	362 kcal	28% (77g)	26% (7.3g)	16% (8.1g)	5% (3.6g)	28% (15.5 mcg)/ 22% (0.498 mg)	21%(0.291g)/36%(0.996g)/23%(0.339g)/29%(0.305g)/20%(0.057g)/23%(0.411g)
Potato flour	357 kcal	30% (83g)	21% (5.9g)	14% (6.9g)	0% (0.3g)	2% (1.1 mcg)/14% (0.313 mg)	21%(0.299g)/16%(0.425g)/18%(0.316g)/27%(0.280g)/41%(0.115g)/20%(0.356g)
Rice flour, unenriched, white	366 kcal	29% (80g)	9% (2.4g)	12% (6g)	2% (1.4g)	27% (15.1 mcg)/ 52% (1.2 mg)	17%(0.244g)/18%(0.488g)/18%(0.317g)/20%(0.21g)/26%(0.072g)/19%(0.348g)
Semolina, unenriched	360 kcal	27% (73g)	14% (3.9g)	26% (13g)	1% (1.1g)	0% / 27% (0.619 mg)	35%(0.490g)/32%(0.867g)/35%(0.616g)/32%(0.335g)/58%(0.162g)/30%(0.540g)

Tapioca, dry, pearl	358 kcal	32% (89g)	3% (0.9g)	0% (0.2g)	0% (0g)	1% (0.8 mcg)/ 5% (0.110 mg)	0%(0.004g)/0%(0.006g)/0%(0.004g)/0%(0.004g)/1%(0.003g)/0%(0.005g)

Table 5. Egg and substitutes calorific and nutritional value comparison. Vitamins / minerals and proteins / amino acids are only listed for the reference base > 20% DV in wheat flour (italics). Source https://www.nutritionvalue.org/; aquafaba estimated from (Kubala, 2017; Stantiall et al., 2018). DV = % Daily Value for a diet of 2,000 calories a day.

Ingredient	**Calories per 100g**	**Total Carbohydrate**	**Protein**	**Fat**	**Vitamins: Pantothenic acid / Riboflavin / Vitamin B12**	**Minerals: Selenium/ Phosphorus**	**Proteins and Amino acids: Isoleucine/Leucine/Lysine/Methionine/Phenylalanine/Threonine /Tryptophan/Tyrosine /Valine**
Egg, fresh, raw, whole	*143 kcal*	*0% (0.7g)*	*26% (13g)*	*12% (9.5g)*	*31%(1.533 mg)/35%(0.457mg)/37%(0.89mcg)*	*56%(30.7 mcg)/ 28%(198mg)*	*48%(0.671g)/40%(1.086g)/43%(0.912g)/36%(0.380g)/39%(0.680g)/ 53%(0.556g)/60%(0.167g)/29%(0.499g)/47%(0.858g)*
Aquafaba (5.13 g solid/100g in pulse cooking water for boiled chickpeas)	Negligible (15ml ~ 35 calories)	0% (1.24g)	1% (0.95g)	0%	Information not available	Information not available – trace likely	Information not available
Baking Soda	0 kcal	0% (0g)	0% (0g)	0%(0g)	0%(0g)/0%(0g)/0%(0g)	0%(0.2mcg)/ 0%(0g)	0%(0g)
Custard (egg custard prepared with 2% milk, dry mix)	112 kcal	7% (18g)	8% (4.1g)	4% (2.8g)	14%(0.683 mg)/18%(0.235mg)/24%(0.58mcg)	9%(4.9mcg) / 20%(137mg)	16%(0.226g)/15%(0.402g)/14%(0.301g)/10%(0.1g)/11%(0.19g)/15%(0.159g)/19%(0.052g)/ 10%(0.181g)/14%(0.26g)
Liquid egg (egg substitute, fat free, liquid or frozen)	48 kcal	1% (2g)	20% (10g)	0% (0g)	33%(1.66mg)/30%(0.386mg)/14%(0.34mcg)	75%(41.3 mcg)/ 10%(72mg)	47%(0.660g)/36%(0.972g)/34%(0.713g)37%(0.387g)/37%(0.645g)/46%(0.484g)/59%(0.164g/26%(0.456g)/44%(0.792g)
Oil (canola rapeseed)	884 kcal	0%(0g)	0%(0g)	128% (100g)	0% (0g)	0% (0g)	0% (0g)

Potato flour	357 kcal	30% (83g)	14% (6.9g)	0% (0.3 g)	9%(0.474mg)/4%(0.051mg)/0%(0 mcg)	2%(1.1mcg)/24%(168 mg)	21%(0.299g)/16%(0.425g)/20%(0.413g)/10%(0.107g)/18%(0.316g)/ 27%(0.28g)/41%(0.115g)/13%(0.224g)/20%(0.356g)
White yogurt (yogurt, low fat, plain)	63 kcal	3% (7g)	11% (5.3g)	2% (1.6 g)	12%(0.591 mg)/16%(0.214mg)/23 %(0.56mcg)	6%(3.3mcg)/ 21%(144mg)	20%(0.286g)/19%(0.529g)/22%(0.471g)/15%(0.155g)/16%(0.286g)/ 21%(0.216g)/11%(0.03g)/15%(0.265g)/24%(0.434g)

Foods providing 20% or more of the DV were considered to be high sources of a nutrient based on U.S. Food and Drug Administration guidelines. Still, it is acknowledged that foods providing lower percentages of the DV also contribute to a healthful diet (U.S. Department of Health and Human Services, 2020).

The survey results were then combined with the environmental and nutritional results such that the most ecological (non-similar) substitute was identified as the one with the best nutritional qualities and least environmental impact from the available data.

Finally, processed foods used by respondents as substitutes for eggs and wheat flour were qualitatively assessed for nutritional adequacy based on literature.

Following data analysis, mitigation strategies were identified in the literature. Then mitigation strategies observed during the COVID-19 lockdown were compared with the literature. Finally, an overarching model for mitigation strategies from farm to fork was developed consisting of observed strategies used during COVID-19 lockdown, theoretical strategies in the literature and proposed mitigation strategies based on gaps between theory and practice.

4. Results

This study aimed to connect consumer behavior with environmental and health impacts during demand-induced scarcity to inform mitigation strategies. Initially, consumer behavior was statistically quantified, followed by quantitative and qualitative assessments of impacts on the environment and nutrition.

The survey attracted 243 respondents. Of these 243 respondents, 222 experienced reduced availability of eggs or wheat flour during the COVID-19 lockdown in the UK, whereas 21 did not. The 21 respondents who did not could have been experiencing lockdown in another country, were not responsible for food acquisition or other reasons. With a sample size of 243 respondents, there is a 6.28% margin of error and 88% confidence level.

In the first section below, an investigation of supply chains for wheat flour and eggs is presented to confirm that the scarcity was demand-induced. This is followed by the results of the survey of consumer behavior in terms of previous literature, environmental impact and nutrition.

4.1 Wheat Flour and Egg Supply Chains

4.1.1 Wheat flour

The total UK wheat harvest was about 13,953 thousand metric tons (t) for the year 2018-19 and produced about 4,949 thousand t of flour (nabim, 2019b). nabim (2019c) further states that 84% of wheat milled in the UK was homegrown, and the rest was sourced from outside the UK. Figure 2 illustrates the distribution of wheat flour milled in the UK (nabim, 2019c). The majority (69%) is destined for bakeries, 10% is used for biscuit making, and 15% is used in other foods, exported or used in cake making. Only 4% of the wheat flour is available for household consumption in shops and supermarkets.

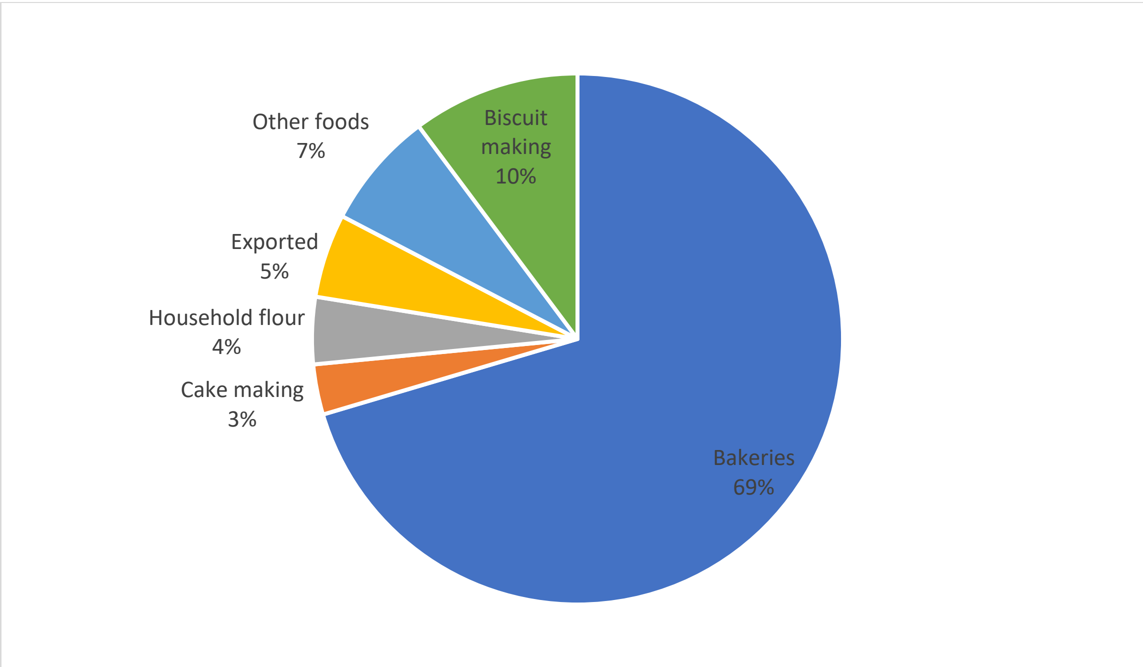

Figure 2. The UK Flour Milling industry

The wheat flour that is produced in bulk and sent to bakeries or other food manufacturers is in either tankers or 16 / 25 kg bags. The wheat flour that UK consumers purchase from shops and supermarkets is usually in 1.5 kg packets. On average, each of the 27.5 million UK households purchases a packet of flour every 14 weeks, but during the COVID-19 pandemic, both bulk buyers and households bought more than usual (Hyslop, 2020). Households engaged in baking activities during the lockdown, which led to an increase in demand for flour. In addition, there was a lack of capacity to pack wheat flour into small bags for shops and supermarkets.

Some households that were unable to obtain wheat flour used substitutes such as almond, chickpea, coconut, rice or spelt flour (Marcus, 2020). The media noted that since the flour industry is better equipped to produce in bulk, selling flour in larger bags should be considered (BBC, 2020).

In conclusion, demand-induced wheat flour scarcity at the retail level in the UK during COVID-19 lockdown could have been mitigated by enabling wholesale to retail transfer of supply. Impediments included packaging and increased demand by bulk buyers.

4.1.2 Eggs

British Lion Egg Processors (BLEP) reported that in 2018, one-third of eggs were sourced by food manufacturers from outside the UK (1 billion eggs annually) (Fortune, 2018). Further, the UK is claimed to be 86% self-sufficient for total egg consumption and could be self-sufficient as there has been a huge increase in the UK flock over the last few years to meet rising demands. This is reflected by the Egg Statistics shown in Table 6 from DEFRA (DEFRA, 2020).

Table 6. UK Packing Station egg throughput by egg production type (thousand cases) (1 case = 360 eggs)

Year	**Q1**	**Q2**	**Q3**	**Q4**	**Total**
2017	7,373	7,498	7,558	7,521	**29,951**
2018	7,654	7,671	7,718	7,900	**30,943**
2019	7,886	7,926	7,998	7,824	**31,633**
2020	7,808	7,698	-	-	**-**

During COVID-19 lockdown, the retail demand for eggs was very high, whereas eggs intended for hotels, restaurants, pubs and other catering industry struggled to find a market. A contributing factor for the low supply of eggs was 'Pancake Day' just before the pandemic (25th February 2020), which depleted egg stocks. Retail demand for eggs was up by as much as 100% in some supermarkets with some egg suppliers to supermarkets experiencing a volume increase in excess of 300% (Ryan, 2020a). Panic buying, stocking up, and lack of resilience in the egg supply chain led supermarkets such as Lidl to stock Dutch eggs to mitigate the shortage. Farm-gate sales of eggs increased by 400% or more, leading some farms to install egg vending machines.

Egg redirection to retailers was insufficient. Packaging, logistics and contractual agreements caused some of the issues with redirection. Better alignment of contracts between retailers, packers and producers could have alleviated the retail availability of eggs (Ryan, 2020b; McDougal, 2020). Other causes were a lack of opportunity to explore the delivery of liquid eggs in cartons to supermarkets and educate consumers to buy them instead of shell eggs to ease pressure on egg supply (Sandercock, 2020).

There were several additional problems in the poultry sector, such as the accessibility of raw materials and other supplies, including bedding, fuel, spare parts and soy feed. These problems were partly caused by temporary closures of saw-mills and small stores as well as disruption at ports in China and India, leading to raw feed materials shipments being delayed (NFU, 2020). This led to an increase in feed price. Feed prices also increased due to exchange rates and the impact of COVID-19 on global logistics chains.

In conclusion, egg production in the UK may be almost self-sufficient. Still, the support for that production relies on both local and global supply chains which consequently affect both availability and price. Improved supply chain practices, including wholesale to retail transfer of supply, and consumer education, would mitigate demand-induced shocks.

4.2 Consumer Behavior

Of the respondents that experienced reduced availability of eggs or wheat flour, 175 did not seek substitutes for egg or wheat flour. Only 44 respondents did. This indicates that although scarcity is experienced, a majority of the population does not seek direct mitigation, and there is support for deferred consumption. Only 31 experimented with a new recipe using substitutes for eggs or wheat flour. Only a very small number of these respondents (9) made a second attempt at a different substitute if the first attempt failed. This illustrates that unsustainable behavior was repeated, but limited as few respondents were willing to exert the additional time and effort. If a new recipe was acceptable, 44 (all) of the respondents made it again. This would indicate a change in behavior pattern in satisfying needs, but only for a minority.

The majority of wheat flour substitutes were necessarily similar (another type of flour) whereas egg substitutes were necessarily dissimilar with the exception of liquid egg. When asked about consuming an alternative food when eggs or wheat flour were not available, 121 out of 205 respondents responded positively, but only 33 listed a dissimilar alternative; e.g., meat, vegetable, milk product, cereal instead of egg; rice, potatoes, pasta, couscous instead of bread. The behavior ranged from a structured approach to changing the meal plan to looking in the fridge/cupboard and consuming what was there. The results indicate a preference for similar substitutes as opposed to varied consumption.

63 respondents bought eggs or wheat flour when they did not need them, but were available. Respondents also bought items such as bread or flour intended for people with intolerances. Although this may be categorized as a forced expenditure or selfish behavior in the literature, it may reflect self-interest without malicious intent due to a lack of knowledge or appreciation of potential consequences.

119 respondents bought wheat flour that was priced more than before the COVID-19 lockdown. This indicates a significant willingness to pay. This is important information for manufacturers/producers who may have increased costs when increasing production.

Quality may mean different things to different people. The survey question referred to product, packaging and quantity as a reflection of quality. Only 35 respondents indicated that the eggs or wheat flour that they purchased were not of equivalent quality to before the COVID-19 lockdown. This may or may not reflect an actual response of food manufacturing/production. Still, there is anecdotal evidence that increased oversight of production should be balanced with the need to feed the country. Food that is a risk to human health would be a concern as this would not produce a benefit and could cause additional fears to spread in the population, potentially leading to antisocial behaviors. Unsustainable production/manufacturing practices also carry risk to workers.

There was a fairly even split among respondents who purchased an equivalent processed food product to what they would have made at home: 81 purchased processed food whereas 90 did not. Therefore, no clear bias towards consumption renaturalization (a diminished processed food role) exists. 45 respondents purchased an unrelated food product, so there is some evidence of forced substitution.

The shadow economy ranges in size from 7.2% to 62.3% of GDP in 158 countries, with an average size of 31.9% (Medina & Schneider, 2018). The UK tends to be at the lower end of that scale. 18 respondents sought eggs or wheat flour on the black/grey market. This indicates the presence of a black/grey market, and a longer period of shortages would likely lead more people to consider this alternative. This is something to be mitigated against, particularly if antisocial behavior is involved.

Table 7 summarizes which of the consumer behaviors investigated based on previous research were present during the COVID-19 lockdown in the United Kingdom.

Table 7. Consumer behavior responses to survey.

Consumer Behavior	**Indicator(s)**	**Percentage (based on total responses per question / total respondents (n=243))**

coping behavior: dietary change	-seeking substitutes -experimenting with new recipes -consumed alternative food	20% (44/219) / 18% 17% (31/186) / 7% 59% (121/205) / 50%
short-term unsustainable measures to increase household food availability	-second attempt at substitution	5% (9/184) / 4%
similar or dissimilar substitutes	-replaced wheat flour with other type of flour (similar) -replaced egg (dissimilar) -dissimilar alternative food	85% (17/20) / 7% (dissimilar: flax seed, oatmeal, polenta) 92% (11/12) / 5% (dissimilar: aquafaba, baking soda, custard and soybean milk, oil, potato starch; similar: liquid egg) 27% (33/121) / 14%
deferred consumption	-did not seek substitute	80% (175/219) / 72%
varied consumption	-consumed alternative food	59% (121/205) / 50%
narrowed consideration set	-sought substitute AND did not consume alternative food	30% (13/44) / 5%
increased time and effort	-seeking substitutes -experimenting with new recipes -second attempt at new recipe	20% (44/219) / 18% 17% (31/186) / 7% 5% (9/184) / 4%
willingness to pay	-purchase of eggs or wheat flour priced more than before COVID-19 lockdown	69% (119/173) / 49%
relatively low quality of production	-product not of equivalent quality to before COVID-10 lockdown	20% (35/173) / 14%
diminished processed food role / consumption renaturalization	-purchasing an equivalent processed food product	47% (81/171) / 33%
selfish behavior	-buying eggs or wheat flour when they were not needed	36% (63/175) / 26%
forced expenditure	-purchasing an unrelated food product	27% (45/167) / 19%
presence of a black/grey market	-seeking eggs or flour on the black/grey market	11% (18/165) / 7%

4.3 Environmental Impact

4.3.1 Food waste

From the survey results, 44 respondents tried new recipes by substituting eggs and/or wheat flour with a substitute ingredient. 16 of them generated food waste while trying the new recipes: 2 respondents always binned the food cooked, and 14 respondents sometimes binned it. Out of these 16 respondents, 9 attempted another recipe with a new ingredient substitution, of which 6 reported that they generated food waste again. This means that 16/219 = 7.3% of the respondents generated some food waste, and 6/219 = 2.7% more than once. Assuming respondents would cook these recipes for their families, extrapolating this proportion to the total number of families in the UK would give 7.3% × 19.2 million families (Office for National Statistics, 2019b) = 1.40 million families generated food waste by trying new recipes. Taking a conservative assumption to presume each time food waste was generated, the equivalent of one cup of wheat flour (~120 g) and one chicken egg (~57 g) was wasted (for both the first and second attempted new recipe), the approximate total food waste generated by trying new recipes was (120 g + 57 g) × (7.3% + 2.7%) × 19.2 million families = 340 t. Out of this number, about 230 t correspond to wheat flour equivalents and 109 t to egg equivalents. For context, UK households generated 6.6 Mt of food waste in 2018, of which 4.5 Mt corresponded to edible parts of food (Parry et al., 2020).

It would be unfair to say that these 340 t of food waste were generated because of trying new recipes since the traditional meals that could have been prepared with wheat flour and eggs could also have generated some food waste. Nevertheless, it is likely this possible egg and wheat flour waste level would have been significantly lower, because of more experience cooking the traditional meals compared to trying new recipes with the substitutes. Anecdotal evidence in the media also suggests that inexperienced cooks with access to flour and eggs wasted food as well due to failed experiments or first-time baking which this data does not account for.

According to the most recent calculations of household food waste generation and management in the UK, it would be expected that local authorities would collect 187 t of the 340 t of food waste generated as residual waste, 41 t would be collected as organics, 6 t would be collected by other means, 78 t would be disposed to sewer, and 28 t would be composted at home (Parry et al., 2020). Food waste collected by local authorities as residual waste and other means would be sent for recovery (thermal treatment to recover energy or landspreading) or in the worst-case disposal (landfill). Food waste collected as organics would be sent for recycling (anaerobic digestion or composting). Projecting the latest statistics available, 37 t would have been sent for recovery, and 10 t would have been landfilled (WRAP, 2020).

Identifying the most sustainable solution to manage a type of food waste can be complex. The food waste hierarchy classifies management options according to their sustainability performance, from high to low: prevention, reuse, recycle, recover and disposal. However, not every type of food waste can be managed via all options from the food waste hierarchy. To identify the most sustainable solution from the food waste hierarchy to manage a certain food waste type, we applied a Food Waste Management Decision Tree. This Decision Tree discards potential food waste management options following UK and European regulations, and classifies the remaining options to minimize environmental impacts and maximize social and economic benefits (Garcia-Garcia et al., 2017). The result of the application of the Decision Tree to the egg and wheat flour substitutes can be seen in Table 8.

Table 8. Categorization of egg and wheat flour substitutes and identification of their most sustainable food waste management solution from the food waste hierarchy. Methodology developed by Garcia-Garcia et al. (2017).

Egg substitute	**Categorization via Decision Tree**	**Sustainable food waste management solution**
Aquafaba, baking soda, potato starch, oil, soybean milk	Edible, eatable/uneatable, plant-based, single product, processed, unpackaged, catering waste	Human consumption/anaerobic digestion
Liquid egg, custard, white yogurt	Edible, eatable/uneatable, animal-based, single product, animal product, processed, unpackaged, catering waste	Human consumption/ anaerobic digestion

Flour substitute	Categorization via Decision Tree	Sustainable food waste management solution
Buckwheat flour, oat flour, rice flour, coconut flour, gluten-free flour, flax seeds, cornflour, semolina, nut flour, tapioca flour, chick pea flour, gram flour (besan), polenta	Edible, eatable/uneatable, plant-based, single product, processed, unpackaged, catering waste	Human consumption/anaerobic digestion

As can be seen in Table 8, all the egg and wheat flour substitutes can undergo the same sustainable food waste management solution, even when they belong to different food waste categories and follow different paths in the Decision Tree (middle column). For each food waste category, two food waste management solutions are presented, as the respondents did not provide information to elucidate if the food waste was eatable or uneatable i.e., they wasted food because they chose not to consume it (because they did not like the taste of the new food product or because they prepared too much) or they wasted the product because it could not be consumed (e.g., burning during cooking, expiring, falling onto the floor, etc.). In the first case, reasonably, food waste should have been consumed by humans as initially expected. This would include options such as being consumed by the cook or people living in the same household, being shared/given to family, friends or neighbors, or being given away to a charity, food bank or similar. When the food could not have been consumed, it should have been sent to anaerobic digestion to produce biogas (for electricity and/or heat generation) and digestate (a fertilizer). If there were no anaerobic digestion plants in the area, the food waste should have been composted, either at home or industrially. Since only 41 t of the total 340 t of food waste generated was collected as organics (and presumably sent for anaerobic digestion or industrial composting) and 28 t was composted at home, it can be concluded that around 80% of the food waste was treated in unsustainable ways, with a more sustainable food waste management solution from the food waste hierarchy being available. This shows the existing potential to optimize household food waste management.

In addition to the aforementioned traditional food waste management solutions, there are other options to maximize the value of food waste, i.e., to valorize food waste. Opportunities have been found to extract valuable compounds from food waste and use them in a wide range of applications, for example, to manufacture new food products for human consumption (Garcia-Garcia et al., 2019). In this way, food waste can be a source of valuable chemicals, materials and fuels (Lin et al., 2013; Pfaltzgraff et al., 2013). Nevertheless, due to cross-contamination with other waste materials and lack of traceability, it is difficult to valorize household food waste, and this option has predominantly been explored in the manufacturing sector (Sheppard et al., 2020).

4.3.2 Life-Cycle Assessment (LCA)

Another aspect to consider when substituting one ingredient with another is the environmental impact associated with producing the original and the substitute ingredient. This means that, depending on the substitute used, the environmental impact of the new recipe can be larger or smaller than for the original recipe.

The environmental impact results for the different ingredients investigated based on responses to the survey (Figure 1) indicate that substituting eggs with oil would increase the environmental impact of the recipe, but substituting them with the other ingredients would reduce it. For flour, the only substitute that could reduce the environmental impact of wheat flour would be corn flour. In general, the environmental impacts of the different products vary significantly.

Not all possible substitutes were included in the analysis because of a lack of data. It must be noted that this environmental impact analysis is intended to be just exploratory and not conclusive. The analysis is preliminary and includes a number of assumptions and simplifications. For instance, different databases were used to collect data, which limits the comparability of the results. The scope considered for the environmental impact associated with each of the ingredients is not always the same. Finally, it must be noted that a lower global warming potential does not mean that the ingredient is more environmentally friendly, because the impact of another environmental impact category may be higher. For instance, eggs may have a lower global warming potential than oil, but higher acidification. To produce clear and conclusive results, a full LCA must be undertaken for each ingredient, which falls out of the scope of this work.

4.4 Nutrition

4.4.1 Wheat flour

The key role that wheat flour plays in the diet is often underestimated. Wheat flour is a major source of carbohydrates, dietary fiber (DF) and micronutrients (Shewry & Hey, 2015). The calorific values of wheat flour and substitutes used by respondents are all in the area of 350 kcal per 100 g except for flax seeds which are considerably more at 534 kcal (Table 4).

From Table 4, selenium may be identified as problematic in terms of simple substitution as no single substitute or combination of substitutes used by respondents could make up for the dietary contribution of wheat flour without increasing portion size (100 g). Other nutrients could also cause concern as ideally a combination of substitutes would need to be utilized as opposed to a single substitute. However, few respondents indicated using multiple substitutes.

Selenium is important to overall health. Low selenium intake is associated with health disorders, including oxidative stress-related conditions, reduced fertility and immune functions, and an increased risk of cancers. Cereals, meats and fish are the main sources of selenium in human diets with cereals and cereal products accounting for 18-24% of total selenium intake in the UK (Tamas et al., 2010). Selenium intake has declined in the UK since the 1970s, and there appears to be less than adequate intake across a wide age range of the UK population (Stoffaneller & Morse, 2015). The data in Table 4 is for North American wheat, so it is important to note that UK-sourced wheat has low levels of grain selenium and is grown on low selenium soils (subject to local variations), contributing to low dietary selenium intake and likely providing a lower DV (Broadley et al., 2006).

The recommended selenium intake in both the UK and USA is similar (cca 55 mcg). The selenium concentration of representative bread-making wheat was estimated to be around one-tenth of the UK recommended intake values for men and women (Adams et al., 2002). Food composition data indicate that white wheat flour in the UK has only 2 micrograms of selenium per 100 g (European Food Safety Authority (EFSA), 2020), indicating that it may provide less than 4% of the DV.

Particularly high risk for selenium deficiency are vegetarians (Adams et al., 2002) or those in situations of reduced income who would not obtain sufficient selenium from meat or fish products due to their greater cost. Concerned with adverse effects of meats, consumer preference for vegetarian diets is increasing worldwide, reaching 20% in the United Kingdom (Alsalman et al., 2020).

Short-term mitigation strategies for selenium deficiency may include supplementation. Selenium content in food and forage crops may be increased through agronomic biofortification with selenium-containing fertilizers providing the best short-term solution on an agricultural scale for improving selenium content of wheat (Tamas et al., 2010). Longer-term genetic improvement may provide a means of enhancing uptake and promoting accumulation. Agronomic biofortification and breeding strategies to combat selenium deficiency have been noted as a possible nutritional intervention for coronavirus infections given the (theoretical) possibility of vaccination-induced anti-body dependent enhancement of disease (Ricke & Malone, 2020; Schiavon et al., 2020). Returning to importation of higher selenium wheats from North America would also be a suitable mitigation strategy, supply chain and market conditions permitting.

From the available environmental impact and nutritional data, corn flour appears to be the best candidate for substitution of wheat flour.

4.4.2 Eggs

Eggs are a rich source of nutrients, including protein, zinc, iron, and vitamins D, B6, and B12. Eggs have high bioavailable protein with a biological value of 100 and net protein utilization of 94 (Hoffman & Falvo, 2004). Moreover, eggs induce greater satiety than carbohydrate rich foods which makes them ideal for breakfast meals (Vander Wal et al., 2005; Westerterp-Plantenga et al., 2012).

In cake and dessert baking, in addition to their color and flavor, eggs are essential for their emulsifying, coagulating and leavening properties (Ratnayake et al., 2011). Consequently, replacement of egg may change not only the nutritional content of a recipe and impact on general health, but also the palatability of the outcome. Substitutes are unlikely to be universal for all recipes.

As indicated by Table 5, it is difficult to find a suitable substitute for egg in terms of nutrition (aside from liquid egg) without increasing the portion size (100 g). The already problematic situation with selenium (see the section on wheat flour) is further exacerbated with egg scarcity. From the available environmental impact and nutritional data, white yogurt appears to be the best dissimilar substitute for egg.

The best mitigation strategies would be increased production as permitted by agricultural capacity and supply chains, and reduced waste informed by the correct application of substitutes that are recipe specific.

4.4.3 Processed Foods

The lack of flour availability during the COVID-19 pandemic meant consumers were unable to bake their own bread, cakes and pizzas or make pancakes. The lack of eggs affected food choices mainly at breakfast (i.e., omelets, English breakfast containing fried/boiled eggs and pancakes). The survey indicates that a significant number of respondents (47%) bought ready-made/processed foods.

Processed foods varied from ‘medium-processed’ that probably have nutritional compositions closer to home-baked foods (e.g., bread) to ‘ultra-processed’ that might contain significant amounts of sugar, fat, salt and additives which make them less desirable from a health/nutritional point of view compared to homemade snacks and meals (Gupta et al., 2019).

The data shows that consumers made some efforts to partially compensate for the nutritional composition of eggs as a source of protein and fat (i.e., choosing meat, dairy-based products, hummus). However, in some cases, processed and carbohydrate-rich foods were consumed instead.

Some consumers purchased products intended for those with food intolerances, e.g., gluten-free bread and flour. If many people adopted this coping strategy, it would be more difficult for people with food intolerances to satisfy their needs. A comparison of Genius Gluten-Free Soft White Sliced Bread 535 g with Hovis Soft Medium Sliced White Bread 800 g indicates that the gluten-free bread has more fat per 100 g (5.2 g versus 1.7 g) and fiber (8.5 g versus 2.4 g), but less protein (1.8 g versus 8.7 g). However, because the gluten-free bread contains egg white as opposed to no egg in the Hovis bread, there may be a slight benefit in terms of nutrients.

In summary, the best mitigation strategy due to the amount of processed food likely consumed is to improve its nutritional value. Consumer information and behavioral norms are also important in reinforcing good eating habits and ensuring people with food intolerances are able to satisfy their needs. Restricting access to food intended for those with intolerances might be problematic.

5. Discussion

This research has connected consumer behavior with environmental and nutrition impacts to collate mitigation strategies that inform production. Surprisingly little is known about consumer behavior during demand-induced scarcity: a Scopus literature search for "demand induced scarcity" and "consumer behavior" or "consumer behaviour" reveals no documents; only five articles concern “demand induced scarcity” in the context of water or energy. This gap motivated the current study as such disruptions may become more frequent due to climate change and political situations: recent examples include food shortages in Northern Ireland (related to Brexit) and Texas (polar vortex). This research is informed by consumer behavior during the COVID-19 lockdown in the UK and seeks ecologically embedded mitigation strategies (Trollman et al., 2020).

Construct face validity is established when an expert on the research subject concludes that the instrument (in this case the questionnaire) measures the characteristics of interest (Bolarinwa, 2015). Criterion validity for the black/grey market question was established by post hoc comparison with the estimated size of the UK shadow economy (Medina & Schneider, 2018). The questionnaire was further strengthened through convergent validity in that respondents were asked to provide qualitative examples to support their responses to questions regarding substitutes and alternatives. Known-group validity supported face validity as the consumer behavior questions were based on previous literature as indicated in Table 1. Face validity was further supported by the feedback of the pilot group (Connell et al., 2018) and post hoc by the clarity of the qualitative responses of respondents.

Self-reporting bias may result from social desirability, recall period, sampling approach, or selective recall (Althubaiti, 2016). To address social desirability bias, the questionnaire was anonymous. The response to the last question, which was most likely to be affected by social desirability bias, aligned with estimates of the shadow economy indicating that social desirability bias was unlikely to be significant. Recall period was addressed by terminating the study when one of the respondents noted inability to recall their actions, and by collecting data as soon as was feasible after the COVID-19 demand-induced scarcity was experienced. The sampling approach faced the issue of self-selection bias. However, self-selection bias was partially controlled as the first question eliminated respondents who had not experienced reduced availability of eggs or wheat flour during the COVID-19 lockdown in the UK. Selective recall was partially mitigated by using qualitative analysis as opposed to quantitative analysis of the reported foods so that it did not matter whether respondents recalled all or only some of the foods consumed. The diversity of responses was supportive of sampling sufficiency.

Figure 3 is a conceptual (economic) model of the interactions among consumer behaviors and production through demand-induced scarcity. Mitigation strategies need to inform both production and consumption with respect to available alternatives to not exacerbate demand-induced scarcity and maintain acceptable levels of nutrition and food waste.

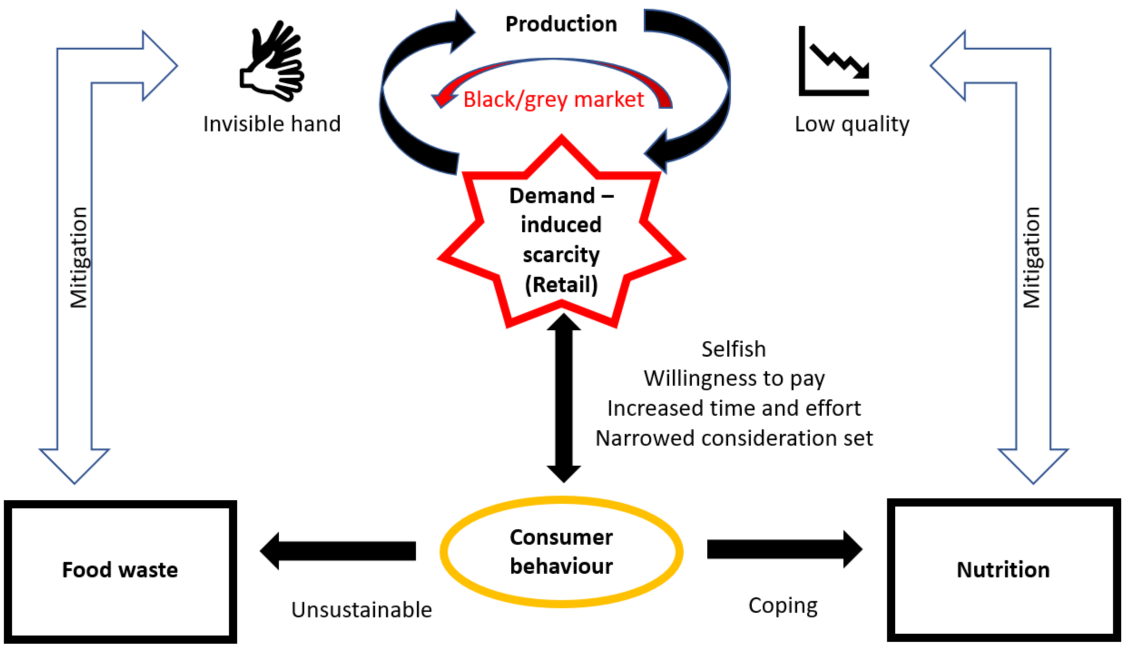

Figure 3. Consumer food waste and nutrition related to production through demand-induced scarcity.

As indicated by the arrows in the figure, some consumer behavior may be considered to have an antagonistic relationship with other consumer behavior(s). Other consumer behavior(s) may act to accelerate both positive and/or negative outcomes synergistically. Table 9 identifies these relationships and notes mitigation strategies.

Table 9. Potential positive and negative synergies between demand-induced scarcity and consumer, producer and retailer behavior; mitigating or enhancing strategies.

	Consumer (C), Producer (P), Retailer (R) behavior	*Effect*	*Mitigation / enhancement strategy: observed during COVID-19 (O), theoretical (T) or proposed (W)*
Negative synergies	Buying more processed food (C)	Reduced health benefits	Improve nutritional value (W)

	Consumption renaturalization (C)	May increase demand for related products causing additional scarcity Reduced income for producers Reduced time for other activities (e.g., employment)	Implement strategies for improving production (O, T)
	Dietary change / varied consumption / similar or dissimilar substitutes (C)	Increased food waste Reduced health benefits	Disseminate information about suitable substitutes, recipes, alternatives (O, W)
	Selfish e.g., purchasing scarce products when not needed / unsustainable measures (C)	Increased food waste Reduced availability of food for people with intolerances Reduced availability of products especially key workers / vulnerable people	Raise awareness of impact on others (O) Limit purchases per household (O) Redirect products to key workers / vulnerable people (O)
	Willingness to pay (C)	Affordability Resources unavailable for other purchases	Provide financial support (O)
	Increased time and effort (C)	Reduced time for other activities (e.g., employment)	Implement strategies for improving production (W)
	Narrowed consideration set / Deferred consumption / Forced expenditure (C)	Poor nutrition	Improve awareness of alternatives (W)
	Participating in the black/grey market (C)	Reduced government revenue Unregulated for consumer protection	Implement strategies for improving production and maintaining reasonable prices (W)
	Donating products not able to retail (e.g., intended for wholesale market) (P)	Supports grey market and reduces demand for similar items from retailers	Direct donations to limited types of organizations (food banks, charities, NHS) (O)
	Increased production (P)	Reduced quality (= lower nutritional value, health and safety risks, increased cost per unit, increased waste)	Ensure affordability through compensation schemes (W) Implement appropriate sustainable food waste management solution (W) Improve production oversight (W) Increase number of workers (O)
	Increase in retail price (P), (R)	Affordability	Provide financial support to economic actors (W)
Positive synergies	Buying more processed food (C)	Reduced food waste	Improve accessibility and affordability (W)

Consumption renaturalization (C)	Alleviates boredom during lockdown Improved health benefits	Encourage and support behavior to mitigate long term scarcity (W)
Dietary change / varied consumption / similar or dissimilar substitutes (C)	Environmental benefits Improved health benefits Reduced food waste	Reinforce behavioral change (W)
Willingness to pay (C)	Improved compensation for producer	Ensure producer benefit is used to further mitigate scarcity (W)
Increased time and effort (C)	Alleviates boredom during lockdown	Educate people on how to use available resources responsibly (W)
Forced expenditure (C)	Improved income of other producers	Encourage responsible consumption (W)
Donating products not able to retail (e.g., intended for wholesale market) (P)	May alleviate scarcity May improve nutrition May introduce consumers to new products Reduced food waste	Offer tax rebates / deductions (O/W)
Increased production (P)	Increased supply	Increasing financial compensation to business/workers (W)

Improving nutritional value can be done at the level of agricultural products through improved soil/animal care and the introduction of soil/feed amendments. The improvement of farming practices through such mitigation strategies is important for long-term sustainability which will help to achieve a co-integrated vision of human, animal and environmental health which includes a circular bio-economy (Barcaccia et al., 2020).

Medium-term responses would include food manufacturing acting to improve the formulation of processed food products, including the addition of supplements. This is particularly important as in the case of eggs and wheat flour, this research has shown that consumers are unlikely to use suitable substitutes, and many rely on processed food alternatives.

The COVID-19 pandemic has illustrated that short-term action may be necessary covering the months of a lockdown period during which people may not be getting daily recommended values of nutrients. Immediate responses would include information campaigns on healthy diets, tested recipes with substitutes to reduce food waste and to signpost appropriate dietary supplements based on analysis of likely nutritional insufficiencies and risk groups resulting from anticipated or observed demand-induced scarcity.

As part of a short-term response, the redirection of local wholesale supply to retail or charity should be supported. A major priority in the design of future strategies and policies as a result of learning from the COVID-19 experience is support for food supply chains built on a place-based approach that examines their local dimensions (Mastronardi et al., 2020). However, it is not possible to avoid a global contribution in many cases. Sourcing products through appropriate global supply chains also has a role in mitigation due to the different nutrient composition of the same agricultural product due to soil composition, etc.

Figure 4 describes the interactions of the aforementioned strategies. Crops, livestock and imports contribute input to food processing. Food manufacturers supply retailers who sell to consumers. Food that is not consumed may be recovered or disposed of. Food may contribute to a nutritious diet leading to good health, or inadequate nutrition may cause health issues. Retailers may inform consumers about expected behaviors, substitutes and their use, and nutrition; retailers may inform food manufacturers about reformulation/supplementation to compensate scarcity. Producers, food manufacturers, and retailers may receive information about consumer health and food waste in order to adopt appropriate mitigation strategies based on available knowledge and advancements as well as relevant time scales.

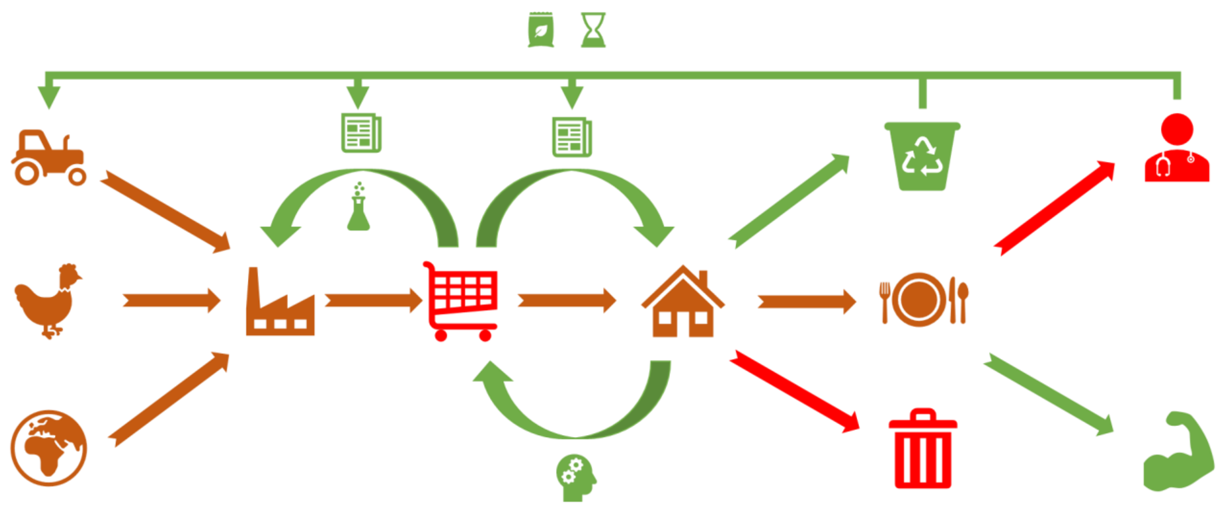

Figure 4. Information and material flow for mitigation strategies due to demand-induced scarcity.

Although there are many concerns and negative perceptions about landspreading biosolids (Collivignarelli et al., 2019), the application of organic materials from food waste specifically could be a valuable source of physical improvements to soil that would otherwise be destroyed by incineration or wasted in landfill (Monteiro et al., 2011). The fertilizer resulting from anaerobic digestion, the best commonly employed environmental treatment identified in this analysis, may lead to a loss of micronutrients such as selenium, iron, zinc and copper because in addition to nitrogen and phosphorus, some micronutrients are essential for anaerobic microbes (Moller & Muller, 2012; Xu et al., 2019).

The appropriate use of digestate is a complex issue needing further study to prevent imbalances in the receiving environments. Previous research has shown that food waste appears deficient in some trace metals such as cobalt and selenium which are required by the anaerobic digestion process at high ammonia concentrations (Banks et al., 2012; Facchin et al., 2013). Hence, these micronutrients may need to be added to facilitate anaerobic digestion, and closing process loops in anaerobic digestion remains a challenge. Furthermore, in anaerobic environments, the formation of elemental selenium (Se^0) is predicted and is commonly considered an unavailable form in natural environments (Nancharaiah & Lens, 2015) in contrast to highly bioavailable selenite and selenate predominant in oxygenated environments (e.g., composting). Consequently, we propose composting and landspreading of food waste or the reoxidation of elemental selenium as an additional step in the treatment of digestate prior to use as fertilizer.

Selenium deficiency is regarded as a major health problem for 0.5 to 1 billion people worldwide (Haug et al., 2007). This research has shown that the UK population, and vegetarians in particular, are at high risk of selenium deficiency. Selenium is a rare resource with unique properties which make it valuable to industry, and efficient recycling is difficult so that selenium added to commercial fertilizers associated with large losses does not reflect careful management of this resource.

The significant reliance of the UK population on processed food during scarcity provides an opportunity for food manufacturers to consider strategic reformulations and blends to satisfy nutritional needs of the population as this is considered an effective practice alternative to agronomic biofortification with fertilizers (Haug et al., 2007; Schiavon et al., 2020). Having adequate amounts of selenium in commonly consumed food products would likely provide greater benefits than direct supplementation as those with the most to gain (e.g., male heavy smokers) are unlikely to take supplements.

Renaturalization of food production was not significantly observed, although this may change for either a prolonged period of scarcity or income loss. These factors could also contribute to grey/black market effects which were also not significantly observed. A failure to maintain the stability of production due to labor shortages, renaturalization of food production, grey/black market, etc. would undermine production further leading to negative economic, health and environmental effects.

Other researchers have confirmed willingness to pay (Wang et al., 2020) and dietary change in general e.g. (Murphy et al., 2020), but the other aspects of consumer behavior presented in this research have not been investigated. Similarly, the importance of selenium has been recognized e.g., (Majeed et al., 2021; Gorji et al., 2021; Heller et al., 2021), but mitigating strategies have not been proposed.

The limitations of this work include simplifying assumptions in interpreting the survey data with respect to the amount of food waste produced and generalizability, lack of availability of certain data in environmental and nutritional databases, and incomplete information about the cycling of metals in anaerobic digestion in the literature. Future work will seek to address these issues by developing a more detailed strategic plan for food scarcity response including more complete LCA, and investigation into treatments of digestate for improved cycling of resources.

6. Conclusion

This research has taken a systems perspective of demand-induced scarcity during the COVID-19 lockdown in the UK. Environmental and nutrition impacts were informed by egg and wheat flour retail shortages. We found that consumers are likely to rely on processed foods and have a limited consideration of alternatives, both of which contribute to nutritional inadequacy. Uninformed consumer decisions may lead to poor nutrition, food waste, and negative environmental impacts. The most notable risk is selenium deficiency which is likely exacerbated by conventional anaerobic digestion. We propose mitigation strategies from farm to fork in support of a circular bio-economy for food production. Our findings suggest agronomic biofortification, breeding strategies, selective imports and improved processed food quality are important mitigation strategies whereas anaerobic digestion of food waste should be re-evaluated.

Future work is suggested in Table 2 which involves the steps of testing and adapting the proposed interventions, and collecting sufficient evidence of their effectiveness for rigorous evaluation. Ideally, these steps would be undertaken in advance of the next shock to the food system. Nutritional interventions such as food reformulation / substitution and the related effects of landspreading could be tested outside of an actual food shortage. Actual changes to consumer behavior could be investigated through simulation on volunteers.

Recommendations for stakeholders include the following:

Better environmental data is needed for LCA of biological products, soil quality maps, food waste disposal, and nutritional content of foods, especially for local conditions, to facilitate a systems understanding. More research is needed into anaerobic digestion and its environmental impacts, again from the systems perspective of ensuring valuable elements are cycled.

Consumers should consider the implications of their choices outside of satisfying their own direct needs. Alternatives or substitutes to usual consumption patterns should be carefully considered to ensure they do not lead to unhealthy choices, food waste, or increased consumption due to needs not being satisfied.

Producers should consider long-term strategies for maintaining soil/animal health which would include working with waste processors to find suitable strategies to support a circular bio-economy.

Food manufacturers should consider improving the dietary benefits and environmental impact of their products to avoid potentially ill-informed legislative changes. Consumption renaturalization is not a significant concern for the type of demand-induced scarcity investigated in this research as consumers are instead likely to rely on processed food alternatives.

Retailers should raise prices if their costs increase (and share the benefit with producers) as this research has shown that consumers are willing to pay in situations of demand-induced scarcity. Multiple strategic redirections of consumers that benefit product availability (as well as consumer health and environmental impacts) through in-store information provision is worthwhile not only for sales and to mitigate pressure upstream, but to compensate for consumers' narrowed consideration set and encourage varied consumption.

Policy makers should facilitate ecologically embedded solutions by sharing information not only across supply chains but, as this research has demonstrated, through integration of environmental and health considerations which may be the responsibility of different parts of government. Also, due to the need for short, medium-, and long-term strategies, appropriate interventions to curb potentially damaging market tendencies are likely to be required.

Acknowledgements

Supplementary Material

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