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by Eastham, J. and Creedon, A.

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REVIEW ARTICLE

Food losses, food waste, and beyond in food supply chains: Retaining optimum nutrient density

Jane Eastham[1] | Annette Creedon[2]

[1]Harper Adams University, Dept of Food Land and Agribusiness Management (FLAM), Newport, UK

[2]British Nutrition Foundation, London, UK

Correspondence
Jane Eastham, Harper Adams University, Dept of Food Land and Agribusiness Management (FLAM), Edgmond, Newport, UK.
Email: jeastham@harper-adams.ac.uk

Abstract

"Food systems" as a concept draws upon systems thinking and facilitates a transdisciplinary approach to address the complexity of delivering the Sustainable Development Goals in developed and developing food regimes. Extant literature has used a food supply chain/systems approach to evaluate sources of food loss and waste (FLW) and their impact on food accessibility and therefore nutrient availability. The maximization of nutrients available to a growing global population is a critical aspect in the sustainable agenda and it is acknowledged that the continued augmentation of food produce is no longer the sole solution. However, there is a drive for greater efficiency, not simply in the resources deployed, but in the utilization of the food produced. This paper argues that FLW are not the only sources of nutrient loss within a supply chain and that there is a loss of nutrient density as the food progresses through the supply chain with the deterioration of nutrients in food within the food supply chain. It is argued here that in parallel to the management of loss and waste, there is a further need for a research agenda to explore the reality of loss of nutrient density holistically as it passes from farm to fork, building on the existing scientific research at each tier within the supply chain.

KEYWORDS

food loss and waste, food systems, nutrient loss, transdisciplinary approach

1 | INTRODUCTION

In 2015, the Sustainable Development Goal (SDG) 2.1 committed global and national institutions to ending hunger and food insecurity by 2030 (FAO et al., 2021), yet, 720–811 million people were faced with hunger in 2020, which was a growth of about 27% from 2019 and indicates limited progress toward achieving either SDG 2.1 of ensuring access to sufficient safe and nutritious food for all people at all times and/or SDG 2.2 of eradicating all forms of malnutrition. World population numbers are estimated to increase to 9.8 billion by 2050 (UN, 2023; Islam & Karim, 2019), and nutrient loss, particularly in the form of food loss and waste (FLW), has been recognized in academic and policy circles as a key focus for interest and research in order to support adequate food supply to meet the concurrent increase in global demand for food (Campoy-Muñoz et al., 2021; Chauhan et al., 2021; HLPE, 2014; Ishangulyyev et al., 2019; Luo et al., 2022; Wang et al., 2021).

Accurate measurement of FLW has proved difficult (Amicarelelli et al., 2021; Bellemere et al., 2017; Spang et al., 2019) and is complicated by the range of definitions attributed to FLW. However, the volume of FLW is estimated to be between 31% and 40% of the food grown globally (UNEP, 2021; WWF, 2021), with 54% of this loss occurring during production and postharvest handling and storage stages (Bellù, 2017). The monetary value of FLW is estimated at about $936 billion (Ishangulyyev et al., 2019) and has been considered a moral issue and a social and economic cost to society (Chauhan et al., 2021; Lohnes & Wilson, 2018; Otten et al., 2018).

While there lacks a universally acknowledged definition of food loss (FL) and food waste (FW), the Food and Agriculture Organization (FAO., 2019) has made the distinction between both. FL is when the loss of quantity or quality of food stems from the decisions and actions by food suppliers in the supply chain and includes food material that is removed as it is in excess of demand or unfit for consumption at harvest, postharvest/storage, processing, and distribution. FW refers to the decrease in the quantity or quality of food resulting from actions and decisions at later stages in the supply chain, for example, retailers, food service establishments, and consumers, and can include the point of distribution (Fabi et al., 2021; Withanage et al., 2021). For the most part, FLW relates to the removal of edible food that is rejected and removed from the supply chain prior to human consumption (Raak et al., 2017; Dora et al., 2021), although FLW can also pertain to inedible byproducts unavoidable in the production of food (Beretta et al., 2013; WRAP, 2009).

FLs are seen to be more prevalent within lesser developed countries (LDCs) as a consequence of poor systems of storage and harvesting, poor infrastructure, and lack of integration with local markets (Bellù, 2017; Bellemere, et al., 2017; Parfitt, et al., 2010). Findings suggest that some 30% of FLW materialize from the production (14%), handling (15%), and storage and processing (1%), whereas FW accounts for just 14% compared with 35% in more developed countries (MDCs) (Bellù, 2017; Ishangulyyev et al., 2019; Lipinski et al., 2013). In MDCs, FLs are less endemic, due to the adoption of more advanced technologies including highly mechanized farming and sophisticated cold chains. In MDCs including the United States and the United Kingdom, FW is more pervasive, as excess food production, operational and supply chain efficiency, quality and food standards, and the variability of consumer demand due to the vagaries of consumer choice and aggressive marketing practices contribute to FLW (Alexander et al., 2017; Bellemere et al., 2017; Bellù, 2017; Bernstad et al., 2017; Canali et al., 2016; Devin & Richards, 2018; HLPE, 2014; Muriana, 2017; Parfitt et al., 2010).

While the loss of nutrients through FLW is generally recognized within policy and academic circles (Ishangulyyev et al., 2019), there is a potential need for further consideration of the losses of nutrient value that arise due to the loss of nutrient density in the food delivered to consumers. Years of scientific studies have researched the factors that result in the loss of nutrients in food; however, none of these studies have taken a holistic supply chain approach (e.g., Brevik et al., 2020; Bulgarelli et al., 2013; Karmas & Harris, 1988; Mercier et al., 2019; Moysiadis et al., 2021; Rodriguez-Amaya & Amaya-Faran, 2021; Spang et al., 2019). Research has focused on the impact of growing conditions (e.g., soil condition and nutrients) and the climate (e.g., rainfall, temperature, and light intensity) on initial levels of nutrients in crops, as well as storage, processing, and distribution, but as yet, there is no research that has identified and quantified the cumulative effect of the conditions of treatment throughout the supply chain on a food product's end nutritional value (NV).

Similar to research that aims to conceptualize FLW as a supply chain issue (Bernstad et al, 2017; Messner et al., 2020; WRI, 2016), a supply chain approach also provides greater insight into the loss of nutrient density in food delivered for human consumption. Extant research presents and argues for a more holistic food system approach to the issue of FLW (El Bilali et al., 2019; Fanzo et al., 2018; Fanzo et al., 2021; Garnett, 2011; Haddad et al., 2016; Messner et al., 2020), and offers the basis for proposed future research into supply chain nutrient density loss. Indeed, extant research into the factors that lead to loss of nutrient density suggests that conditions and practices that result in FLW in the food system are similarly "hotspots" for the loss of nutrient density in consumable food and would therefore be the key points within the supply chain to target in order to optimize the retention of nutrients.

Both FLW and nutrient density loss are, and should be, a key concern to a range of policy makers with remits of influence within food supply chains. Meanwhile, research into the loss of nutrient density calls for greater collaboration across a range of disciplines interested in the uptake and preservation of nutrients throughout the supply chain. In essence, this paper calls for a transdisciplinary supply chain approach to evaluate the levels of nutrients in the food delivered to the consumer. Research into this phenomenon could consider all food supply chains, whether extended, short, or alternative.

This paper argues that in line with the emphasis in current policy on the food systems, there is a need for a more holistic approach to nutrient loss within food supply chains. With the aim of maximizing the availability and accessibility of nutrients, addressing FLW is seen to be a way forward, but there is also room to consider the nutrient value and the extent of loss of the food that is delivered to the consumer. The paper is designed to open the debate around the loss of nutrient density and to discuss some of the existing research that might be drawn upon in a transdisciplinary approach.

2 | THE NOTION OF FOOD SYSTEMS IN THE CONTEXT OF MALNUTRITION

The United Nations (UN) SDGs put forward under the Paris agreement in 2015 aim to alleviate hunger and poverty and to ensure health and well-being for all in a more resilient and equitable food system by 2030. This has led to the demand for a more holistic consideration and metrics to deliver healthy, affordable, sustainable, and culturally acceptable diets, that is, "food systems."

However, between 702 and 828 million people globally were affected by hunger in 2021. Having been relatively unchanged since 2015, the prevalence of undernourishment rose from 8% in 2019 to 9.3% in 2020 and continued to increase at a slower rate in 2021 to reach 9.8%. Global hunger has been exacerbated by factors such as the global pandemic (COVID-19), conflict, and economic shocks affecting markets globally. In 2021, hunger affected 278 million people in Africa, 425 million in Asia, and 56.5 million in Latin America and the Caribbean

(20.2%, 9.1%, and 8.6% of the population, respectively). It is estimated that 8% of the world population will be undernourished in 2030, the same percentage as in 2015 when the 2030 agenda was launched. Food insecurity also remains high and around 2.3 billion people in the world were moderately or severely food insecure in 2021 (nearly 30% of the global population), which is an increase of more than 350 million people since 2019. The prevalence of severe food insecurity increased to 11.7% in 2021, which is an increase of 207 million people in a 2-year period and highlights a significant increase in pressure on existing food resources (FAO et al., 2022). Events such as COVID-19, the blockage of the Suez Canal, and indeed the war in Ukraine have further highlighted the vulnerability of supply chains and the potential inaccessibility of sufficient food sources.

While international trade is seen to contribute to food availability by covering shortfalls in domestic supply and increased food availability in LDCs (Van Berkum 2021; Van den Broeck & Maertens, 2016), as well as contributing to foreign exchange earnings, there is evidence to suggest that although higher income levels can be attained, there is doubt that benefits attained are passed on to the Indigenous population (Van den Broeck & Maertens, 2016). With less food grown for home consumption and increased dependency on food imports and inflated global food prices, issues of food availability and accessibility are heightened (De Hoyos & Medvedev, 2011; Patel-Campillo, 2010).

The notion of food systems as a means of holistically conceptualizing the delivery of food is an attempt to devise an integrative approach to health and food policy and brings new insights into addressing the problem of food security (Fanzo et al., 2021; Jones & Ejeta, 2016; Pinstrup-Anderson, 2013). It is well recognized at a global level that improvements to life expectancy and reductions in child mortality are in part attributable to improved access to food and dietary intake, although an increased life span does not necessarily correlate with good health.

According to the Global Burden of Disease (IHME, 2023), non-communicable diseases (including cardiovascular disease and musculoskeletal and mental disorders) were responsible for 1.62 billion DALYs (disability-adjusted life years) in 2019, which is an increase from 43% in 1990 to 64% in 2019. Nutritional deficiencies resulted in 49.8 million DALYs and 252,000 deaths in 2019 and caused 9.79 million DALYs in children aged 1–5. What is also evident is that there are significant health inequalities and lower life expectancies between different groups within society (Dixon & Everest, 2021; Olivera et al., 2022; Otu et al., 2020; Popkin et al., 2012).

The measures and initiatives under the label "food systems" consider the need as defined by both SDG 2, which commits to end hunger and enable the delivery of food security, to improve nutrition, and to promote sustainable agriculture, and SDG 12, which focuses on sustainable consumption and production, the management of FLW, and the development of policy to promote these agendas. SDG 2 and SDG 12 are closely associated with the "optimization of nutrient density." With growing global populations, access to safe nutritional food is dependent not only on the agricultural production of larger volumes of food, but on the coordination and management of food production in order to minimize FLW and nutrient density loss in the context of increasingly contested resources of land, energy, and water (Jones & Ejeta, 2016; Lemaire & Limbourg, 2019; Palmisano, et al., 2021).

TABLE 1 Sustainable Development Goal 2 (extracted from UN Department of Economic and Social Affairs, 2021).

2.1		Universal access to safe and nutritious food
2.2		End of all forms of malnutrition
2.3		Double the productivity and incomes of small-scale food producers
2.4		Sustainable food production and resilient agricultural practices
2.5		Maintain the genetic diversity in food production
2.6	2a	Invest in rural infrastructure, agricultural research, technology and gene banks
	2b	Prevent agricultural trade restrictions, market distortions and export subsidies
	2c.	Ensure stable food commodity markets and timely access to information.

TABLE 2 Sustainable development goal 12 (extracted from UN Department of Economic and Social Affairs, 2021).

12.1	Implement the 10-year framework of programs on sustainable consumption and production, all countries acting, with developed countries taking the lead, taking into account the development and capabilities of developing countries
12.3	By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses
12.7	Promote public procurement practices that are sustainable, in accordance with national policies and priorities
12.a	Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production.

Yet, the emphasis of SGD 2 SDG 2 (as seen in Table 1 below), is on agricultural practices, investment in innovation in agricultural practices, and sustainable access by farmers to markets. The emphasis is that sufficient nutrition should be delivered through the augmentation of production or, less explicitly, through the implementation of propagation techniques to enhance nutritional content.

SDG 12 focuses on the issue of sustainable consumption and specifically identifies FW and the reduction of FL from the perspective of the food supply chain and supply chain influencers (Table 2 below). It also highlights the need to examine sustainable patterns of production and consumption in more detail. All of these factors are critical issues with respect to the provision of sustainable nutritious food for an increasing global population and are a function of all tiers of a supply chain.

However, despite the wealth of multidisciplinary scientific investigation into the practices that lead to the deterioration of nutrients at each tier—from preharvest through to processing, storage, and distribution—the loss of nutrient density is ill recognized within the UN agenda.

Emphasis on nutritional loss through FLW is clearly identified in SDG 12 and, as such, is reflected in current agri-food and food science research. Yet, in this paper, we call for an investigation into both dimensions of loss of nutrient density as a supply chain issue, not simply as a theoretical exercise, but to deliver a real-time practical

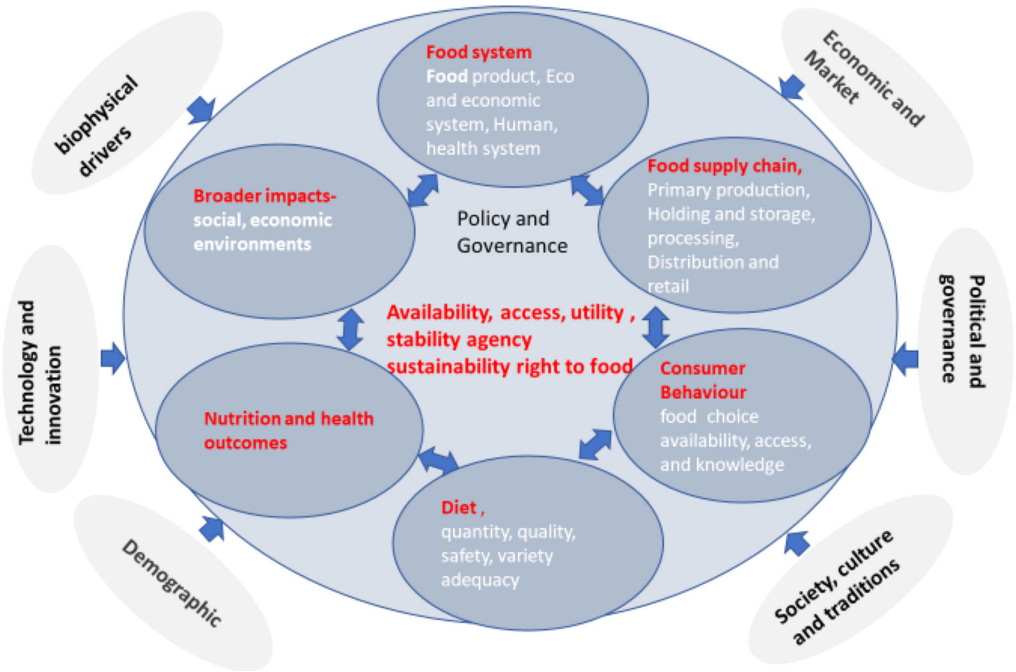

FIGURE 1 The food system. Adapted from HLPE (2020).

understanding of "hotspots" or the location of hazard points (i.e., where the loss is most prevalent), with a view to reviewing practice. The location of critical hazard points will be specific to supply chain structures and product characteristics and provenance and they will vary according to season and weather conditions in any year or month. This suggests that there is a need to uncover where the losses occur to minimize loss of nutrients and product quality and to have a clearer insight into the dynamics of the supply chain and the triggers for such loss and thus maximize the nutrients retained.

3 | SHIFTING TO A HOLISTIC FOCUS ON NUTRIENT LOSS THROUGHOUT SUPPLY CHAINS

Research into the deterioration of nutrients is in the main reductionist, focusing on single processes or supply chain tiers. The concept of food systems, however, presents a conceptual integrity that in the context of production, farming, processing, and global supply chains presents a framework for the evaluation of the economic, social, and environmental impacts of food production, although the environmental impact is not a focus of this paper (Van Berkum et al., 2018). Figure 1 depicts the concept of food systems and represents the complexity of the nexus of the policy areas/decisions, and their relationship with societal, economic, and environmental challenges. In addition, the value of the food system approach is that it allows for consideration of the interconnectivity between those challenges as considered in the meso-level analysis put forward by Bellù (2017).

The food systems framework is underpinned by Systems Theory (Emery & Triste, 1965; Von Bertalanffy et al., 1968), thereby allowing the shift from traditional approaches to societal and economic challenges, from the reductionist perspective to a holistic framework. The reductionist approach is argued to extract the subject of observation from its environment, while a more holistic approach enables exploration of the interrelationships between parts and how they form the complex field of interconnected factors. Systems theory and thus food systems take a transdisciplinary view, enabling the emergence of further knowledge and understanding.

Bellù (2017) in his work on the causes of FLW classifies these in terms of micro, meso, and macro levels. While micro-level causes of nutrient loss are attributed to the actions of agents at the same tier of the supply chain (e.g., poor harvest scheduling and timing), systems thinking and the concept of food systems allow the conceptualization of nutrient loss from the perspective of the functioning and coordination of the whole food chain. This is referred to by Bellù (2017) as meso-level causes. A further factor that may be important in future research into this area is those causes that stem from inadequate infrastructure (e.g., road systems, cool chains) and other macro-level environmental factors (Bellù, 2017). While this paper is predominantly interested in micro- and meso-level factors, it is suggested that the root macro-level factors such as lack of adequate infrastructure may be, in many cases, the issues to address.

4 | FOOD SYSTEMS AND LOSS OF NUTRIENT DENSITY

The food supply chain elements of the food system can be roughly classified into tiers of primary production (including pre- and postharvesting), handling and storage, and distribution and retail, and although not addressed here would also include consumption.

It is acknowledged in this paper that although consumers have a major role in determining their food choices, irrespective of the dietary behaviors of consumers, there is a need to synchronize analysis throughout all tiers of the supply chain with a view to examining where losses undermine the optimization of NV delivered to the consumer. In essence, the argument is that the food chain could be more tightly aligned to supporting nutritional recommendations.

Attention has been paid to the importance of food systems and supply chain practices for shaping human health and nutrition, with partial success (e.g., Gillespie & van den Bold, 2017; Haddad et al., 2016; HLPE, 2016; HLPE, 2020; Kuhnlein et al., 2006; Van Berkum et al., 2018; Willett et al., 2019). Research and the management of factors affecting nutrition, or indeed recognition of the need to improve NV, are taking place within agriculture, logistics, food processing, and delivery. Beyond climatic conditions such as exposure of products to light, temperature, rainfall, season, and location, human interventions in primary production, as in the use of fertilizers, can also generate nutritional loss (Mostafa et al., 2008). Even in the harvesting process, there can be a risk to nutrient content through vitamin loss as a consequence of cutting, chopping, shredding, and indeed bruising, all of which will result in exposure to enzymatic activity that catalyzes the degradation of vitamins. Furthermore, early harvesting of products such as paw paw and other fruits can also result in low levels of essential nutrients (Boussaa, et al., 2019; Galli, et al., 2009).

Even where foodstuffs have optimal nutritional levels at the point of harvest, the process of distribution and processing can have an impact on the nutrient density of food consumed. For example, vitamin stability may be of prime consideration in global supply chains that are elongated in both time and distance. Chemically, the vitamins are a heterogeneous group of compounds with no common structural attributes; some are single compounds (e.g., biotin), while others (e.g., vitamin E) are large groups of compounds; and the stability of the individual vitamins varies widely from the relatively stable, in the case of niacin, to the relatively unstable (e.g., vitamin C). The stability of vitamins, particularly the water-soluble vitamins, is also influenced by a number of factors including temperature, moisture, oxygen, pH, and oxidizing and reducing agency of the presence of other vitamins, which can take place at all tiers within a supply chain. Vitamin deterioration can take place naturally during the storage of vegetables and fruits as seen in the gradual reduction of the vitamin C content of potatoes, and losses can occur during the processing and preparation of ingredients and foods, particularly those subjected to heat treatment (Keijbeets & Ebbenhorst-Seller, 1990; Lee & Kader, 2000). Vitamin B12 is particularly sensitive to light and the presence of ascorbic acid and niacin as well as the acidity/alkalinity of the cooking medium for instance. The factors that affect the degradation of vitamins are the same whether the vitamins are naturally occurring or are added to the food from synthetic sources (Brevik et al., 2020; Bulgarelli et al., 2013; Igwemmar et al., 2013; Karmas & Harris, 1988; Mercier et al., 2017; Moysiadis et al., 2021; Orlien & Boulmar, 2020; Rodriguez-Amaya & Amaya-Faran, 2021).

5 | FACTORS AFFECTING NUTRIENT QUALITY IN PRE- AND POSTHARVEST TIERS

Existing research that looks at meeting the SDGs at a "micro level" (Bellù, 2017) across the agro-food sector focuses particular attention on nutrient enhancement associated with postharvest tiers but does not take account of the impact of all practices within the supply chain. However, there is now a stronger interest in the relationship between agricultural agronomical practices and human nutrition, with key areas of focus being range and types of crops grown (DeClerk et al., 2011) and the importance of biofortification of crops on nutrient availability (Carazo et al., 2021; Garg et al., 2018; Khush et al., 2012) and soil nutrient quality (Welch et al., 2013), of which the most extensive body of research is focused on the biofortification of crops and particularly focused on LDCs. As discussed in more depth in 5.1, the issue around soil nutrient quality and available nutrients is coalesced, with recent key investigations in agronomy associated with soil management and precision farming with practices such as integrated crop management and regenerative farming, which at present look to improving resource in line with the remit of SDG 2.3 and 2.4 while also reducing environmental impact.

5.1 | The status quo and beyond in postproduction tiers

As discussed earlier, the status quo in postharvest tiers as explored in food science, food technology, and human nutrition looks at the interrelationship between the conditions of holding/storage and processing, and the nutritional and chemical changes have been investigated (Bender, 1978; Karmas & Harris, 1988; Orlien & Bolumar, 2020; Rodriguez-Amaya & Amaya-Farfan, 2021). Such foci have been single or connected tiers and without a detailed examination of the deterioration of vital nutrients throughout the entire supply chain of a specific product. Yet, were there a means of tracking nutrients within the supply chain, much in line with the procedures adopted with lean thinking, foods would retain more optimal levels of nutrients. Evidence from research by a range of scientists including research into nutrient loss through FLW indicates different hazard points in LDCs compared to MDCs.

Messner et al. (2020) suggest, with reference to MDCs, a leaner approach to supply, which reduces excess supply and subsequently results in fewer requirements for storage or the management of green waste. The position held is that matching the flow of produce more closely with demand would reduce levels of overproduction and wastage in production, handling/storage, and distribution/retail and this could lead to higher levels of nutrient retention in terms of the nutrient composition of the food supplied. The clear link between FLW and loss of nutrient density is a small but important connection as it is the recognition that the longer the supply chain, the greater the risk of deterioration (enzymic and nonenzymic), including NV, of the foodstuffs.

5.2 | Moving the farming agenda forward to incorporate nutrient value

Farming research in MDCs (Mondal & Basu, 2009; Say et al., 2018; Pivoto et al., 2018) has focused on technologies and practices designed to provide efficient profitable production that is economical, viable, and environmentally responsible. One critical area of research has focused on digital solutions such as smart farming and precision agriculture and has emphasized the use of information and communication technology in the cyber–physical farm management cycle (Moysiadis et al., 2021, Saiz-Rubio & Rovira-Más, 2020; Walter et al., 2017; Weiss et al., 2020). Precision agriculture emerged as a consequence of the search for digital solutions in a digital age, stimulated by engineering research into robotics and artificial intelligence technology. This opened up research avenues that have examined the value of the capture of field data in order to target treatments to reduce the use of water, fertilizer, seeds, herbicides, and insecticides based on data obtained with global positioning systems (GPS) and geographic information systems (GIS) technologies (Gupta, 2020; Lal, 2020; Linaza et al., 2021; Mostafa et al., 2008; Saiz-Rubio & Rovira-Más, 2020; Walter et al., 2017; Weiss et al., 2020).

While fertilizers and other chemicals have been over many years seen to be a way of increasing yield, precision and smart agriculture facilitate and are embedded in principles of integrated crop and farm management that have an emphasis on greater efficiency of input use (Patnaik et al., 2020). Integrated crop and farm management can also focus on soil management and linking the impact of macro- and micronutrients and soil health. The value of soil management relates to both the uptake of nutrients by plants and the impact not only on yield but also on improved plant health and nutrients that are thus available to animals and humans (Padgitt et al., 2001). Given the recognition of the role of integrated crop management in improving plant health and the corroborative relationship between plant health and nutrient content, there is a need to better integrate soil ecology and agronomic crop production with human health, food/nutrition science, and genetics as well as a need to effectively communicate soil and human health connections to the broader society. Such research is of equal significance in MDCs as it is in LDCs, where the issues of food insecurity and chronic malnutrition are found in greater evidence.

6 | CONCLUSION

While different tiers within supply chains have undertaken research and taken measures to deliver foods to the consumer, there is still potential to optimize and retain nutrient value within the food produced. The emphasis on work undertaken in the realm of SDGs 2 and 12 has led to a heavy focus on production volume and the reduction of the environmental impact of agriculture. Now it is more generally recognized that simply increasing the volume of food in line with the growing population is not enough to ensure the accessibility, availability, and utility of food; instead, this paper proposes that there is a need to take a holistic approach to the supply chain and in real terms identify the hazard points for nutrient loss, using a multisectoral, transdisciplinary approach. In calling for a transdisciplinary supply chain approach, there is a need to harmonize the expertise of a range of stakeholders including academics, industry, influencers, and policy makers to maximize the level of nutrients that are retained within the food that is ultimately delivered to the consumer.

Bringing the food system into the nutritional discourse enables a greater understanding of the mutual interconnectivity and produces a more holistic approach that offers so much worth to our understanding of how the supply chain can retain and deliver optimal nutritional density for the consumer. It needs to be recognized that this paper is still bounded with limited consideration of the impact of consumer food choices on their actual nutritional uptake. However, this does not detract from this more holistic transdisciplinary exploration of the concept of nutrition loss as a food systems issue.

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CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest to declare for this publication.

ORCID

Jane Eastham https://orcid.org/0000-0003-2021-5589

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