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The role of supply chains for the sustainability transformation of global food systems

A large-scale, systematic review of food cold chains

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Abstract

Global food systems need an urgent transformation to be compatible with sustainable development. While much of the recent academic discussion has focused on food production and consumption, food supply chains have received considerably less attention. Here, we conduct a large-scale, systematic literature review of 48,014 academic articles to assess the links between the food cold chain literature and sustainable development. We find a multitude of deep links between food cooling and the Sustainable Development Goals (SDGs), but also identify underexplored areas of sustainable food cooling research regarding its (1) goals, (2) analytical depth, and (3) context specificity: There is a limited understanding how several relevant synergies between SDGs can be captured, how to best design sustainable food cold chains across multiple value chain stages, and how to scale sustainable cold chains in low-income and lower-middle-income country contexts. We recommend to explicitly consider the salient interconnections between SDGs, increase the analytical depth by deploying more system-level approaches across entire value chains, and focus on localized solutions in contexts where food supply chains are most underdeveloped.

KEYWORDS

cold chains, food supply chains, Great Food Transformation, industrial ecology, sustainability transitions, sustainable food systems

1 | INTRODUCTION

The global food system is in urgent need of a decisive shift toward sustainability, dubbed the Great Food Transformation in the recent literature (Willett et al., 2019). Over 820 million people do not have a sufficient food intake, and many more eat unhealthily. Current food systems are a significant threat for planetary well-being in terms of biodiversity loss, and account for 34% of global greenhouse gas (GHG) emissions

(Crippa et al., 2021). Challenges are set to increase given the need to sustainably feed a projected 10 billion people on the planet in 2050. Crucially, sustainable food systems are not only a prerequisite to achieving the UN's Sustainable Development Goal (SDG) on ending hunger (SDG2), but are closely connected to a large variety of other SDGs (UNEP & FAO, 2022; Willett et al., 2019).

The recent literature on the Great Food Transformation has focused almost exclusively on sustainable food production and consumption, with food supply chains receiving considerably less attention (Food & Agriculture Organization of the United Nations (FAO) 2018; Herrero et al., 2020; Searchinger et al., 2019; Springmann et al., 2018; Weitz et al., 2014; Willett et al., 2019). However, food supply chains are known to be critical enablers for wider food system sustainability transition (Bursová et al., 2018; Kendall & Spang, 2020). A particularly challenging case for achieving sustainable food systems are food cold chains where food needs to be stored, processed, and moved in temperature- and humidity-controlled environments (Heard & Miller, 2019; James & James, 2010; Ravishankar et al., 2020): Due to the high energy demand of cooling food, food cold chains account for over 2% of global GHG emissions, similar to emissions from global aviation, with food refrigeration alone being responsible for 1.7% of global GHG (Crippa et al., 2021). This figure is set to increase as global installed food cooling capacity is estimated to grow by an average 7.8% p.a., three times faster than global GDP (Heard & Miller, 2019; The World Bank, 2022). The rapid cold chain capacity growth is driven by demand increases for perishable food, the need to replace outdated refrigeration infrastructure in industrialized countries (JLL, 2020), and increasing cold chain demands and access in emerging economies. Cold chain coverage rates are at around 20% in China (Hu et al., 2019), and below 10% in many low-income (LIC) and lower-middle-income countries (LMICs) (FAO & IIR, 2016; Heard & Miller, 2019; UNEP & FAO, 2022). While perishable food is key to ensure sufficient nutritional quality and food safety globally (Adesogan et al., 2020; James & James, 2010; Obiero et al., 2019), loss of perishable food in the supply chain alone can reach 40% in some LIC contexts (Wu et al., 2019).

Despite these challenges and impacts, the question of how food cold chain research needs to be designed to yield critical insights on how to drive sustainability transitions has not been assessed in the literature (Niles et al., 2018; Shashi et al., 2018; Vrat et al., 2018; Willett et al., 2019). On the one hand, existing conceptual food cooling research has either not considered sustainability at all (Ali et al., 2020; Cheng et al., 2017; Coombs et al., 2017; Tassou et al., 2010; Zhu et al., 2019), or limits sustainability to a proxy of lowering energy intensity and GHG emissions (Dong et al., 2021; Ghoulem et al., 2019; Han et al., 2021; Heard & Miller, 2016; James & James, 2010; Ndraha et al., 2018; Shashi et al., 2018; Vrat et al., 2018). On the other hand, the sustainable food system transformation literature either does not discuss food cold chains (Food & Agriculture Organization of the United Nations (FAO) 2018; Herrero et al., 2020; Springmann et al., 2018; Weitz et al., 2014), or merely mentions them as a lever to limit food losses (Searchinger et al., 2019) and a cause of GHG emissions (Hu et al., 2019; Niles et al., 2018). Indeed, the 2022 IPCC AR6 WGIII report mentions cold chains as a potentially important lever for climate change mitigation, but classified its recommendation with "limited evidence" due to a lack of research on the topic (IPCC, 2022).

In this paper, we make three main contributions to the literature to address this gap. First, we build on the industrial ecology (IE) literature to suggest a framework for designing food supply chain research for sustainable development (Section 2). Second, after briefly discussing the methods of our critical literature review (Section 3), we systematically assess the current food cooling literature along our framework and discuss salient knowledge gaps in terms of the goals, analytical depth, and context specificity of cold chain research for sustainable development (Section 4). Third, we propose a research agenda to address these gaps and enable food cold chain designs to become a driver of wider food system sustainability transformations (Section 5).

2 | FRAMEWORK TO ASSESS FOOD SUPPLY CHAIN RESEARCH FOR SUSTAINABLE DEVELOPMENT

Food supply chains with their physical food and energy flows as well as their societal impacts are key for shaping the well-known links between the food system and broader themes of sustainable development (Willett et al., 2019). They thus need to be analyzed and designed considering these systemic links. IE concepts are well suited in this regard as they analytically uncover interactions between systems, and quantify resulting environmental and wider sustainability impacts (Baldassarre et al., 2019; Boons & Howard-Grenville, 2009; Erkman, 1997; Seuring, 2004). Designing supply chains to achieve sustainable development has been an important and long-standing component of IE (Allenby, 1992; Huber, 2000). Building on Robért et al. (2002) and Korhonen (2004), as well as some more recent contributions (Baldassarre et al., 2019; Chandrakumar et al., 2019), we derive an analytical framework to design food supply chain research for sustainable development. Specifically, our framework consists of three critical associated analytical features, namely (1) the broadness and interconnectivity of the underlying goals, (2) the analytical depth, and (3) adequate consideration of context specificity. These three components are discussed in turn below.

First, the IE literature suggests that a broad set of social, environmental, and economic goals need to be considered when designing industrial systems. Korhonen (2004) points out that IE conceptualizes industrial systems as being dependent on wider social systems, which in turn are subsystems of the planetary ecosystem. Both the symbioses to the socio-ecological environment of industrial systems (Ayres & Ayres, 2002; Ehrenfeld & Gertler, 1997; Erkman, 1997; Saavedra et al., 2018) as well as evaluating progress toward wider social and economic goals (Figge & Hahn, 2005; Hoffman, 2003; Robèrt et al., 2002; Schroeder et al., 2019) have long been key traces of the IE literature. Hence, researchers have underlined the usefulness of IE concepts toward achieving sustainable development objectives (Allenby, 1992; Huber, 2000; Sullivan et al., 2018). Specifically, Sullivan et al. (2018) show that IE links industrial systems to all 17 SDGs individually (see also Schroeder et al., 2019). Crucially, the IE literature points to the need to identify and evaluate interdependencies between different relevant goals (Chandrakumar et al., 2019; Yang et al., 2020), with a particular focus on "uncovering" existing synergies (Chertow, 2007). Such a broad, recursive, and SDG-oriented framework is particularly well suited to inform the goals of food supply chain design as it aligns closely with the system-wide sustainable development objectives of the Great Food Transformation (Willett et al., 2019).

Second, the IE literature points out the critical importance of in-depth, holistic analyses for designing sustainable supply chains (Ayres & Ayres, 2002; Ehrenfeld & Gertler, 1997; Erkman, 1997; Hoffman et al., 2014). As early as 1992, Allenby defined IE as "*the means by which a state of sustainable development is approached and maintained*" (Allenby, 1992, p. 56). Much of the early seminal work on IE has pointed out the importance of considering all stages of supply chains as well as all of their salient multi-facetted environmental, social, and economic system impacts (Ehrenfeld, 2000; Hoffman, 2003; Lowe & Evans, 1995). IE methods are required to "work at high levels of process and commodity detail" (Pauliuk et al., 2017) in order to fully understand how supply chains drive sustainable development. Hence, a paradigm of conducting in-depth and holistic analyses for sustainable development has emerged from the IE literature which emphasizes the importance of analyzing sustainability both across the entire supply chain and in terms of multiple levels and interactions among various types of impacts (Chandrakumar et al., 2019; Geels, 2011; Pauliuk et al., 2017). Analytical holism is especially crucial in the context of food supply chains as their connection to the SDGs is inherently multi-facetted for each major supply chain stage: They need to be able to deliver on the emerging system-wide strategies to transform food production and consumption (Niles et al., 2018; Willett et al., 2019), contain value adding components such as processing and storage which high proportions of low-income households in developing countries depend on for their livelihood (Alonso et al., 2018; Mujuka et al., 2020), and ensure food logistics capable of meeting existential human needs while operating within economic and environmental constraints (Crippa et al., 2021; Heard & Miller, 2019).

Finally, the IE literature suggests that evaluating the impact of industrial interventions on sustainable development greatly depends on the geographic context they are implemented in (Korhonen, 2004). Seuring (2004) points out that IE's key distinctive feature when compared to other environmental management approaches is its regionality and geographical approach. Geographic variations and case-specific conditions profoundly shape the nature and strength of the linkages between industrial, social, economic, and ecological systems (Chandrakumar et al., 2019; Jensen et al., 2011), the type of impacts they have (Jensen, 2016), and sustainability goals they need to serve primarily (Rahman et al., 2022). This principle of context specificity is salient for the case of global food supply chains as food often passes through regions with highly different socio-economic conditions (Chandrakumar et al., 2019; Gold et al., 2017). Key contextual factors to consider in logistic implementation and evaluating impact include the underlying unequal infrastructure and socio-economics systems as well as the case-specific types of primary value addition activities which define food value chains in different world regions (Maloni & Brown, 2006; Trienekens, 2011).

To summarize, the IE literature implies the merits of combining (1) goals with (2) analytical depth and (3) context specificity to evaluate the types of insights a given research study produces for the food supply chain and sustainable development nexus. These three components form the structure of an evaluation approach of extant food supply chain research in terms of producing insights for sustainable development. Section 3 discusses the methodological details of this approach, applied to the case of food cold chains which this paper focuses on.

3 | METHODOLOGICAL OUTLINE

In this section, we provide an outline of how to translate the framework presented in Section 2 to the case of the cold chain literature in order to assess its nexus to sustainable development in terms of its goals, analytical depth, and context specificity. Specifically, we pursued a five-step logic:

1. We identified the sample of food cooling research articles to be assessed. Due to the large empirical diversity of food cooling as a subject, we implemented an encompassing full-text search tool of the relevant academic literature. The details of this tool are described in Supporting information S1–S3. Our search yielded 48,014 food cooling articles.
2. We derived the subset of food cooling articles linked to sustainable development. We used the full-text search tool implemented in the previous step to search for sets of SDG-specific keywords and counted their compounded hit frequency to determine whether a paper was linked to a given SDG (see Supporting information S1, S3 and S4 for details). We identified 3144 of the 48,014 food cooling papers (6.5%) to be linked to sustainable development. In our results section, we present exemplary evidence of various different links between food cooling and each of the relevant SDGs analyzed by summarizing papers with particularly frequent keyword hits related to the given SDG. However, it should be noted that it is not our intention to fully describe all impact facets food cooling has on sustainable development.
3. In accordance with the IE-informed evaluation approach discussed above, we then identified the goals, analytical depth, and context of food cooling for sustainable development. In terms of goals, we used our full-text search tool to determine the number and types of links to relevant SDGs discussed in the literature (Supporting Information S1 and S3). In terms of analytical depth, we used the full-text search tool to specify the number of supply chain stages addressed by each paper, and contrasted these numbers between the set of papers with and without links to sustainability (Supporting Information S1). This helped us to understand how holistically sustainable food cooling research has addressed different supply chain stages vis-à-vis the general sample. We also coded the prevalence of different types of relevant SDG sub-goals for every sustainable food cooling paper and matched them with the supply chain stages. In terms of context specificity, we used our full-text search tool

to determine the papers' country cases (Supporting Information S1) to identify context-specific hotspots of these links. The results of these analyses are presented Section 4.1.1 for goals, Section 4.2.1 for analytical depth, and Section 4.3.1 for context specificity.

4. We aggregated individual per-paper results to determine key trends in the sustainable food cooling literature for each of the three components of the IE-informed evaluation approach, and assessed these trends against the findings from the analyses in step 3. In terms of goals, we evaluated the frequency and type of SDG linkages as well as the degree of interconnectedness between them. In terms of analytical depth, we assessed the frequency and type of supply chain stages covered as well as the type of SDG-specific sub-goals linked to different supply chain stages. In terms of context specificity, we contrasted the geographic distribution of sustainable food cooling research with the location of some of the largest gaps to reaching the SDGs linked to food cooling. The results of these analyses are presented in Section 4.1.2 for goals, Section 4.2.2 for analytical depth, and Section 4.3.2 for context specificity. To illustrate the results of our meta-analysis, in both the result and conclusion sections, we also present selected exemplary evidence of particular findings by summarizing papers with particularly frequent keyword hits related to the given topic we discuss, that is, where this topic was particularly salient.
5. We derived recommendations for future research where we identified salient gaps between the literature's trends and what our IE-informed evaluation approach has suggested to be relevant in terms of goals, analytical depth, and context specificity of sustainable cold chain research. These recommendations are presented in Section 5.

4 | ASSESSING FOOD COOLING RESEARCH FOR SUSTAINABLE DEVELOPMENT

This section analyzes the food cooling literature (Supporting Information S1, S2, S3) across the three components of the integrated IE-informed approach for assessing food supply chains for sustainable development discussed in Section 2, namely (1) goals, (2) analytical depth, and (3) context specificity. These three components are discussed in three subsections below, respectively, and each consist of two parts, subsequentially presenting the results from step 3 and step 4 described in Section 3, respectively.

4.1 | Assessing goals

4.1.1 | Goals of food cooling for sustainable development

Using our systematic, full-text search tool, we find that food cooling is connected to all of the 15 individual SDGs we have investigated. Table 1 provides illustrative evidence and references of this connection by listing two exemplary and non-exhaustive links between food cooling and each of the SDGs investigated, sourced from papers with particularly close links to the specific SDG (indicated by high frequency of associated keyword hits—see Supplementary information S1). For most of the SDGs, the literature describes how sustainable development can benefit from food cooling, while in some instances, it has also produced evidence of trade-offs. For instance, cooling food is required to limit malnutrition (SDG2) and foodborne illness (SDG3), however, if food cooling systems are highly unreliable, they also carry the risk of increasing foodborne illness through a false sense of security (Table 1). It furthermore enables higher income for (SDG1), balances seasonalities in food retail and gastronomy (SDG8), and decreases food loss and waste which can reduce food system GHG emissions (SDG12 and SDG13). Food cooling infrastructure has been found to help reduce national-level income inequality (SDG10), reduce off-grid energy costs by monetizing productivity gains from avoided food loss (SDG7), and improve predominantly female workers' productivity in low-tech food value chains (SDG5). Crucially, integrating food cooling into energy and transport sector planning enables systemic synergies: The cold of natural gas transport can be used productively in food cold chains rather than dumping it into water bodies (SDG14), and urban freight transport can be minimized through optimal cold storage placement (SDG11). However, critical trade-offs to sustainable development also exist such as health hazards which can affect women disproportionally (SDG5) or biodiversity through fostering industrialized agriculture (SDG15).

4.1.2 | Assessing SDG broadness and interconnectedness trends in sustainable food cooling research

Crucially, while it reports on a large multitude of SDG links, the literature suggests that some links are considerably more salient than others: Discussing the nexus between climate change and food systems (SDG13) makes up more than one third of the entire sustainable food cooling literature (Figure 1). The next most salient SDG connections to food cooling are clean energy usage (SDG7), the health impact of inadequately refrigerated food (SDG3), gender-specific implications of food cooling (SDG5), and the importance of cold chains for sustainable production and consumption (SDG12). Notably, while agriculture accounts for about 40% of global land usage and is the primary source of income for roughly two billion people, systemic connections between preserving perishable food and land usage, income generation, sustainable innovation, and even malnutrition in different LMIC contexts appear to remain largely unexplored.

TABLE 1 Exemplary synergies and trade-offs between food cooling and sustainable development.

SDGs	Exemplary links to expanding food cooling
SDG1	• *Synergy*: Access to food refrigeration is linked to income generation in small-scale food retail and entertainment in communities with poor infrastructure endowments (Mazzone, 2020) • *Synergy*: Food loss from absent cooling infrastructure can reduce smallholder farmer income in low-income countries (LICs) (Pohlmann et al., 2020)
SDG2	• *Synergy*: Cooling infrastructure is a critical means of avoiding an underrepresentation of perishable food in the diet, thereby decreasing different malnutrition risks (Obiero et al., 2019) • *Synergy*: Freezing fresh fruits and vegetables directly after harvest can help retain micronutrients (e.g., in spinach) (Rickman et al., 2007)
SDG3	• *Synergy/trade-off*: Food cooling is essential to limit the health dangers of foodborne illnesses (Ali et al., 2020), but dysfunctional cold chains can give a false sense of security and increase risks of foodborne illness (Sadhu, 2018) • *Synergy*: Private companies co-develop food and vaccine cooling service offerings due to the strategic and operational synergies for providing access to both in LICs (Ravishankar et al., 2020)
SDG4	• *Synergy*: Adequate usage of refrigeration to preserve perishable food has been found to be positively associated with education levels and literacy rates (Madaki & Bavorova, 2019) • *Synergy*: A lack of perishable food in diets increases the risk of impaired growth and development in children (stunting) (Balehegn et al., 2019), a condition most common in regions with limited food cooling infrastructure
SDG5	• *Synergy/trade-off*: By reducing food losses, cold chains can improve (predominantly female) worker productivity in food processing, but can also increase associated cold-related injuries if there was insufficient protective equipment (Nag & Nag, 2007) • *Trade-off*: Frozen fish consumption can expose women of childbearing age to hazardous concentrations of methylmercury (Chan et al., 2018)
SDG6	• *Synergy*: Freezing water can both provide food cooling and desalinate seawater, creating synergies where both fresh drinking water and cold chain coverage are low (Messineo & Panno, 2008) • *Trade-off*: Water, including in remote locations with scarce water resources, is used for both drinking and food cooling, either directly applied onto the surface of the food or in cooling plants where frozen water is the cooling medium (van Haute et al., 2015)
SDG7	• *Synergy*: Monetizing the productivity gains from food cooling infrastructure installed in conjunction with off-grid energy systems can lower the cost of electricity for off-grid customers in LMICs (Haney et al., 2019) • *Synergy*: Integrating renewable energy generation with cryogenic energy storage in refrigerated warehouses can improve food cooling and balance variabilities in power grids with high intermittent renewable energy shares, improving system reliability (Fikiin et al., 2017)
SDG8	• *Synergy*: The lack of cold chain coverage in emerging markets can destroy substantial economic value (Hu et al., 2019) • *Synergy*: Cold chains enable warm countries to sell high-value food items that ensure continued levels of consumption in food retail and gastronomy industries, especially during winter months of colder countries (Hospido et al., 2009)
SDG9	• *Synergy*: Technological innovations of food storage, processing, and monitoring are capable of ensuring more sustainable food system infrastructure (Herrero et al., 2020) • *Synergy*: In rural areas of LMICs, food cold chain expansions have had synergetic effects for the wider public service infrastructure (Haney et al., 2019)

(Continues)

TABLE 1 (Continued)

SDG10	• *Synergy*: Food losses due to a lack of cold chains can exacerbate income inequalities as they tend to primarily affect small-scale, low-income farmers which limits their ability to market their products (Pohlmann et al., 2020) • *Trade-off*: Ownership of food cooling assets is highly unequally distributed both between and within countries (Ravishankar et al., 2020)
SDG11	• *Synergy*: Integrating food cooling centers into sustainable city planning and installing them in a designated, consolidated area reduces urban transport requirements and pollution (Wu & Haasis, 2018) • *Synergy*: In places of rapid urbanization, cold chain expansion from food-producing areas into cities can be critical for urban dweller welfare (Hamilton et al., 2014)
SDG12	• *Synergy*: Expanding cold chains helps to reduce high post-harvest food losses in food supply chains, especially in LMICs (Wu et al., 2019) • *Synergy*: Broad access to domestic food cooling and appropriate food cooling behavior are critical to lower consumer-level food waste (Porat et al., 2018)
SDG13	• *Trade-off*: The high electricity, fossil fuel, and F-gas demand of cold chains has a significant global greenhouse gas emission footprint (Heard & Miller, 2019) • *Synergy*: Depending on context, lowering food losses by expanding cold chain coverage may be able to reduce the overall greenhouse gas footprint of the food system (Hu et al., 2019)
SDG14	• *Synergy*: Cold chains can absorb cold energy from liquefied natural gas production, reducing the amount of cold energy transferred to water bodies next to gasification plants and thus reducing the impact on marine ecosystems (Messineo & Panno, 2008) • *Trade-off*: Expansion of global cold chains may make overfishing more feasible and profitable as extra fish can be stored and sold (Al-Busaidi et al., 2016)
SDG15	• *Synergy*: By reducing food losses, cold chain infrastructure can reduce the negative impacts of food production on the life on land such as land degradation and biodiversity loss (Porat et al., 2018) • *Trade-off*: Expanding cold chain infrastructure can lead to an intensification of industrialized agricultural systems which are known to have adverse effects on biodiversity (Heard & Miller, 2016)

Critically, the literature exhibits relatively low levels of SDG interconnectivity (Figure 1). Roughly 80% of the sustainable food cooling literature is focused on the interaction with one specific SDG (Supporting information S4), suggesting that the extant literature has not been focusing on exploring how to capture value across multiple SDGs simultaneously. Powering cold chains with low-carbon energy (SDG7) to reduce their climate footprint (SDG13) is the prevalent interlinkage between any two SDGs (see Figure 1), being explored by 0.5% of all identified food cooling papers. All other pairwise SDG links are discussed in less than 50 articles, the vast majority of which in less than 5 articles. The analyses uncover a small but noteworthy emerging cluster of five SDGs in the context of the water–energy–food nexus (SDGs 6, 7, 8, 12, and 13) which demonstrate the merits of systemically considering SDG interconnections simultaneously. Within this cluster, Mazzone (2020) for instance suggests how food cooling is a key part of water–energy–food systems when assessing them along environmental, social, and economic criteria. The work by Luqman and Al-Ansari (2020) exemplifies emerging design approaches within this cluster, developing an integrated decentralized solar- and biomass-based energy system that simultaneously delivers food and space cooling, clean water, and heat for domestic and food drying, and doing so significantly more efficiently than providing all these services by themselves. Other related research shows that through systems integration, cooling food can both provide ancillary services to electricity grids (Fikiin et al., 2017) as well as help fostering sector-wide energy efficiency measures (Neusel & Hirzel, 2022), both implying GHG emission savings potential. However, this cluster does not appear to fully capture the synergies and trade-offs to several critical related sustainability issues such as poverty (SDG1) and food access (SDG2) in the context of food cooling: In our entire sample, we identified only four articles linking SDG1 and SDG2 focusing their scope on African cases, with all four articles suggesting that these links are highly context specific (Berger & van Helvoirt, 2018; Hirmer & Guthrie, 2017; Kroll et al., 2019; Shiferaw et al., 2014). In general, there is little examining synergies

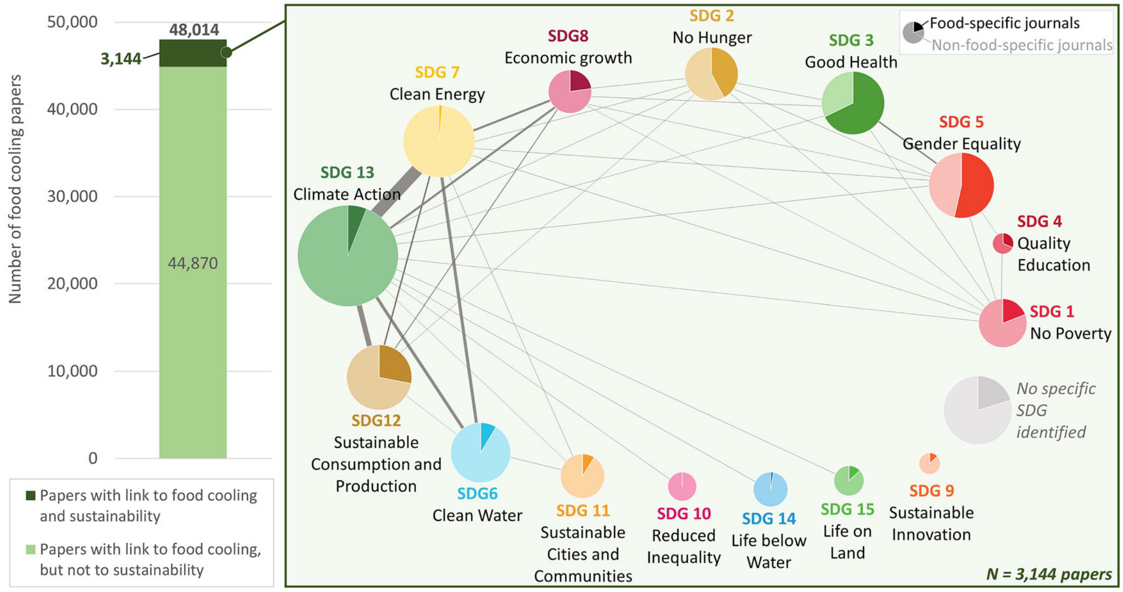

FIGURE 1 Sustainable Development Goal (SDG) linkage types, distribution, and strengths within the sustainable food cooling literature. *Notes*: The bar chart to the left indicates that 3144 of the total 48,014 identified food cooling papers also possess links to sustainability. The thickness of the arcs is proportional to the number of papers addressing the respective two SDGs in conjunction, with the thickest connection between SDG13 and SDG7 representing 248 such papers. Only those connections are shown where more than five sustainable food cooling papers jointly relate to two SDGs. The pie charts indicate the share of papers published in food-specific versus non-food-specific journals for every SDG. The journal classification is taken from Web of Science. The area of the pie charts is proportional to the square root of the number of papers identified with a link to the specific SDG (1235 papers for SDG13). A paper is defined as having an explicit link to a given SDG if it contains at least five cumulative mentions of any combination of terms associated with the SDG in the full text of the paper (see Supporting Information S1, S3). Underlying data for this figure are available in tab "data_from_figure_1" of the Excel file Supporting Information S5.

and trade-offs across more than two SDGs (Supporting information S4). Cold chain design optimization approaches are mostly limited to minimizing carbon emissions, and almost exclusively do not include social criteria.

Notably, the research published in food-specific journals (Supporting Information S1) is particularly prone to not considering sustainable development links: It is more than seven times more likely for a food cooling paper published in a non-food-specific journal to be linked to sustainable development than for one that is published in a food-specific journal (Supporting information S4). Measured against its total share, food-specific journals are underrepresented in every SDG, and contributed less than 10% of relevant research for SDG6 (clean water), SDG7 (clean energy), SDG10 (reduced inequalities), SDG11 (sustainable cities and communities), SDG13 (climate action), SDG14 (life below water), and SDG15 (life on land) (Figure 1). There thus appears to be a noticeable silo within food scholarship which has not focused on producing insights about food cooling-enabled sustainability transitions across the breadth of the supply chains.

4.2 | Assessing analytical depth

4.2.1 | Analytical depth of food cooling for sustainable development

Our analysis finds that food cooling is linked to sustainability on every individual of the seven stages of the food cold chain we have coded, namely production, storage, transport, processing, retail, consumption, and end-of-life. Some SDGs are salient across the entire supply chain: For instance, articles linked to any one of the seven supply chain stages are also more likely to contain links to SDG5, SDG7, SDG8, and SDG 13. All stages of food cold chains feature female workers and beneficiaries with specific needs (Adesogan et al., 2020), require significant amounts of energy, often designed to come from renewable sources (Yokokawa et al., 2019), create economic value (Roibás et al., 2015), and have multiple sources of GWPs (Hu et al., 2019). To provide comprehensive insights on how to design cold chains compliant with these SDGs, there thus appears to be merit in holistically analyzing supply chains. For instance, research has shown that using dewatering technologies which reduce weight, save transport and refrigeration costs, and reduce GHG emissions, are most effective when implemented on-farm (Augustin et al., 2013). Other SDGs appear to be more concentrated in certain specific cold chain stages: For instance, studies linking food cold chains with social SDGs such as income and poverty (SDG1), hunger (SDG2), and health impacts (SDG3), albeit being present across the value chain, are considerably more frequent at the consumer

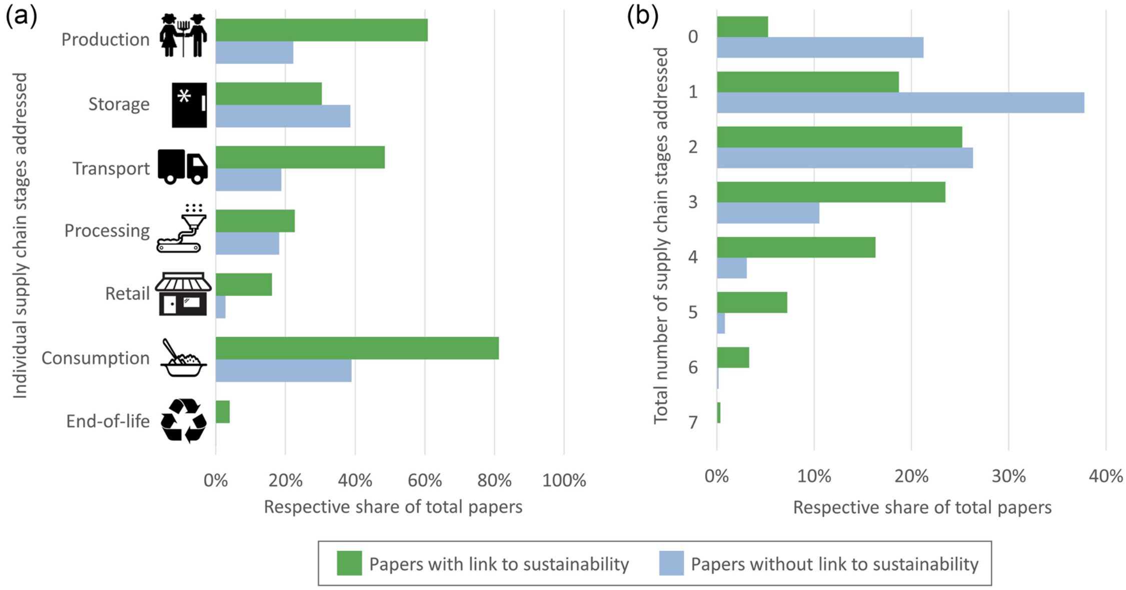

FIGURE 2 Links to distinct supply chain stages (a) and total number of supply chain stages covered (b) of the food cooling literature by whether or not articles are linked to sustainability. *Notes*: Using our full-text search tool (Supplementary information S1), we coded the presence or absence of seven different supply chain stages for every food cooling paper in our sample, namely production, storage, transport, processing, retail, consumption, and end-of-life. The sample included 48,014 papers in total, 3144 of them linked to sustainability, the rest without such a link. Underlying data for these figures are available in tabs "data_from_figure_2A" and "data_from_figure_2B" of the Excel file Supporting Information S5, respectively.

stage which analytically focuses on households in terms of consumer-specific cost of refrigeration (Evans et al., 2014; Dizon et al., 2019), domestic food waste implications for low-income households (Vermeulen et al., 2012; Vittuari et al., 2017), or the design of food assistance programs (Tranchant et al., 2019; Trotter et al., 2020). Indeed, we find this household/consumption stage of the supply chain to be critical for identifying links with sustainability in general: Slightly over 80% of all papers linking food cooling to sustainable development exhibit links to this stage, compared to less than 40% of the food cooling literature without such links (Figure 2a).

Consistent with arguments in the conceptual IE literature (Section 2), we find evidence of the links between sustainability and food cooling being particularly salient when studies address multiple supply chain stages: Each stage except for storage (which often addresses technical and biochemical details of food storage), papers with links to sustainability address every distinct supply chain stage more frequently, and in most cases considerably more frequently, than papers without such links (Figure 2a). The average number of supply chain stages addressed papers almost doubles from 1.4 to 2.7 when comparing food cooling papers without and with links to sustainability, respectively (Figure 2b).

4.2.2 | Assessing analytical comprehensiveness trends in sustainable food cooling research

While the literature suggests that food cooling exhibits a large variety of links to sustainable development across the supply chain, our analyses suggest that it is tilted toward specific types of links (cf. Figure 3). Several of these imbalances are linked to SDG-specific focus areas on specific supply chain stages rather than assessing SDG impacts holistically. For instance, for SDG8, macro-level issues such as job creation and economic growth are almost 10 times more frequently discussed than supply-chain-level productivity or efficiency gains. Similarly, almost 90% of all papers with links between food cooling and SDG12 discuss "food waste," commonly associated with retailers and consumers, rather than supply-chain-level "food loss." Yet avoiding food loss in the supply chain is known to be a critical issue for several SDGs independent of context (Heard & Miller, 2019; Hu et al., 2019), as well as for food security in LMICs, specifically (Affognon et al., 2015). For SDG2, SDG6, and SDG7, retail and customer-specific insights for how cold chain design and deployment can make food, water, and energy accessible and affordable are rare in the literature, despite the known synergies between food, water, and energy access and food cold chains (see Table 1 for details).

As for SDG13, the most frequently mentioned SDG in the food cooling literature, the literature has focused on climate change mitigation, with adaptation featuring in less than 5% of SDG13-relevant articles (Figure 3). This is despite the potential of cold chains to adapt food supply chains to hotter and more extreme weather (James & James, 2010; Yang et al., 2020). The majority of SDG13-related research either only mentioned the impact of climate change on global food systems, or the climate impact of food waste without further analyzing it in great depth. We identified only 26 quantitative analytical papers which study how to mitigate the GHG impact of cooling food across the supply chain. Classifying these articles by

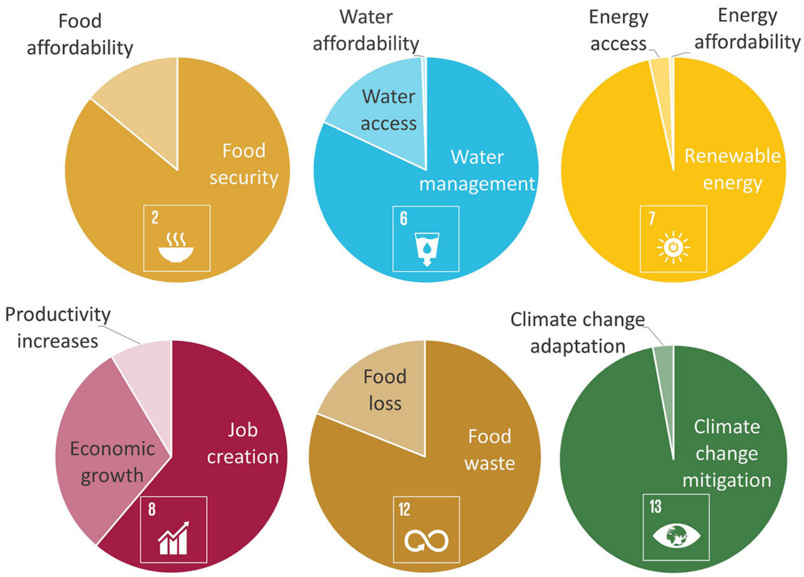

FIGURE 3 Relative shares of the dominant Sustainable Development Goal (SDG)-specific sub-topics of key SDGs with direct links to supply chains mentioned in the sustainable food cooling literature ($N = 3144$ articles). *Note*: Underlying data for this figure are available in tab "data_from_figure_3" of the Excel file Supporting Information S5.

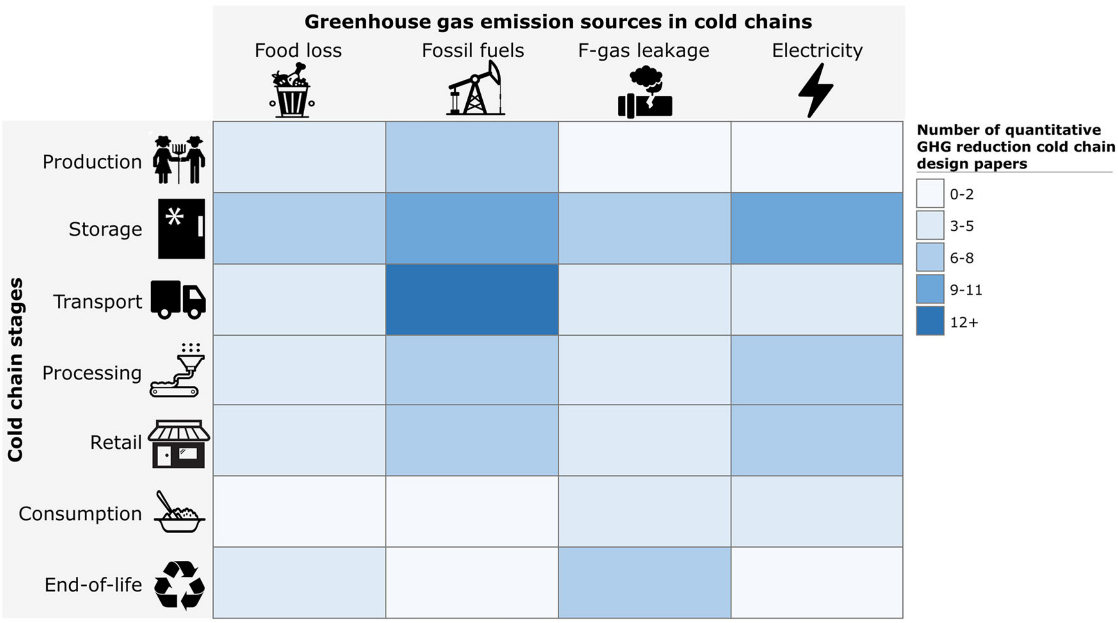

FIGURE 4 Focus areas of the dedicated quantitative cold chain decarbonization literature. *Notes*: Searching the full text of all identified food cooling papers related to SDG13 ($N = 1235$) yielded 26 papers with an explicit quantitative design analysis focus on greenhouse gas emissions of food cold chain systems. All papers discussed more than one of the seven cold chain stages, and the majority addressed more than one GHG source. Underlying data for this figure are available in tab "data_from_figure_4" of the Excel file Supporting Information S5.

cold chain stage and GHG sources yielded an imbalanced picture (Figure 4). The literature is often focusing on GHG emissions of a certain source or supply chain stage rather than a holistic approach. The majority of articles uses inventory and routing optimization of cold chains, and focus on fossil fuels as well as electricity as GHG sources in transport and intermediate storage (Parker et al., 2018). By contrast, there is a paucity of research aimed at integrated food loss mitigation strategies, limiting F-gas leakage and avoiding GHG emissions related to the end-of-life stage. These gaps are particularly noteworthy due to the high respective GHG emissions footprint of food loss and waste, the large GHG potential of F-gases, and the significant shares of food system GHG emissions which occur at end-of-life stages (Crippa et al., 2021; Dreyfus et al., 2020).

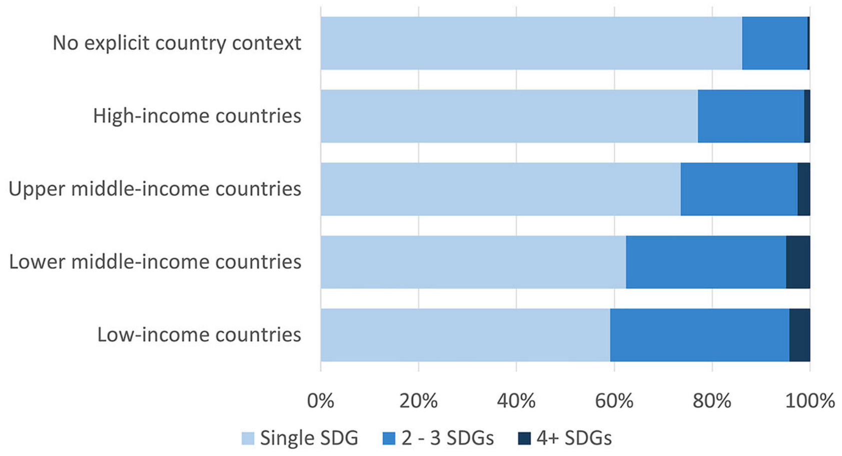

FIGURE 5 Number of Sustainable Development Goals discussed in the sustainable food cooling literature for different types of country cases (*N* = 3144 research articles). *Note*: Underlying data for this figure are available in tab "data_from_figure_5" of the Excel file Supporting Information S5.

Yet, implementing integrated approaches to cold chains are critical to uncover synergies between these issues: For example, centralized cooling systems that act as a hub between fishers/farmers and the market have been suggested as a cost-efficient way of limiting food loss in LICs which can be financed through forming farming cooperatives (Trotter et al., 2020). Crucially, such larger systems also have numerous GHG-related and technical benefits: They limit direct GHG emissions through minimizing potential sources of leakage, enabling easier monitoring (Francis et al., 2017), and by allowing for lower impacts of leakages by switching to low-GWP refrigerants which function better in large systems due to their low volumetric capacity (McLinden et al., 2020). Furthermore, they limit indirect GHG as larger chillers can achieve higher coefficient of performance than smaller distributed chillers, and allow for more efficient end-of-life disposal (Francis et al., 2017). Finally, large systems possess technical advantages such as allowing multiple target temperature for blast freezing, ice production, and cold storage by combining several low-GWP refrigerants, which is not possible in smaller applications (Saini et al., 2022). Pooling and selling multiple cooling services in one site implies added revenue streams for cooling providers which imply advantageous business model implications critical to scale such services in places with low cooling coverage (Trotter & Brophy, 2022). Finally, holistic approaches are key to study adequate end-of-life strategies, for instance deciding between retrofitting extant cooling systems with drop-in low-GWP refrigerants or completely replacing the cooling system, especially in remote parts of the world where access to low-GWP refrigerants can be restricted (Hart et al., 2020).

While studying energy efficiency in individual companies is relatively well established in the literature (Neusel & Hirzel, 2022), understanding such measures along the temperature-controlled cold supply chains holistically is still in an early stage: Critically, this nascent literature has led to contradictory results: Hu et al. (2019) find that expanding cold chains lowers net GHG emissions as the GHG footprint of increased energy demand is more than offset by avoiding emissions linked to food losses (Hu et al., 2019). By contrast, Heard and Miller (2019) find the opposite and report net positive GHG emissions of expanding cold chains. While the reason may be differences in assumptions and empirical settings, the full mechanisms behind these different results have not yet been fully understood. The associated uncertainty places caveats on the quality of strategic direction the current literature is able to offer for sustainable food cold chain design approaches.

4.3 | Assessing context specificity

4.3.1 | Context specificity of food cooling for sustainable development

Both the IE and the wider sustainability transition literature suggest that assessing impacts of actions aimed at increasing sustainable development requires a deep understanding of the geographical context given substantial regional variations in SDG gaps (Truffer et al., 2015). Our results suggest that the importance of food cooling for sustainability is indeed highly dependent on the wider socio-economic context. Specifically, context is key for defining both how many of the SDGs are relevant, as well as the types of SDG linkages. We find LMICs to feature particularly diverse links between food cooling and sustainable development (Figure 5, Table 1). Roughly 20% of all articles addressing a LMIC also exhibit links to sustainability, compared to 6% for the rest of the food cooling literature. Furthermore, Figure 5 shows that over 40% of sustainable food cooling studies relating to LICs analyze more than one SDG, a figure that drops to 23% for high-income countries (HICs) and 13% where no concrete country case is discussed. This suggests that applying food cooling research to a concrete case helps to uncover and study links and impacts of food cooling and sustainable development. Specifically, the LMIC context allows researchers to uncover direct impacts of food cooling and social SDGs (for instance on no poverty [SDG1]; Mazzone, 2020, no hunger [SDG2]; Hirmer & Guthrie, 2017, education [SDG4]; (Sudershan et al., 2008), and gender equality [SDG5]; Wong et al., 2018).

It should be noted that in addition to analyzing geographic context, we also grouped papers by the type of food to be cooled (vegetables, fruits, meat, dairy, and fish) and found no evidence of significant differences in links between food cooling and the SDGs for different types of food. This seems to suggest that geography is a stronger driver of food cooling SDG links than the type of food to be cooled.

4.3.2 | Assessing the adequacy of context focus trends in sustainable food cooling research

While the salience of links between food cooling and sustainable development in LMICs warrants in-depth analyses to study sustainable cold chain designs, LMICs are heavily underrepresented in food cooling research. Only 8.5% of all identified food cooling papers have at least one LMIC-affiliated author. This number is slightly lower than the 9.5% LMIC authorship share a Scopus search reveals for all indexed research articles related to food. Furthermore, LMICs are only explicitly addressed in 2.5% of food cooling research. India alone accounts for roughly two thirds of these figures. The first author and country case study shares drop to 0.1% and 0.25% for LICs, respectively. For 42 of the 79 total LMICs, and entire clusters of countries for instance in Central and Sahelian Africa, we did not identify a single food cooling paper. As our results suggest a high degree of context specificity of the food cooling and sustainable development nexus, these empirical blind spots risk limiting our understanding of how this nexus operates. They are especially meaningful given the considerable deficits in many LMICs with respect to reaching a range of SDGs closely connected to food cooling (Figure 6). In addition, we find that the share of papers with at least one LMIC-affiliated author increases to 9.9% when only those food cooling papers are considered which have a link to sustainability, suggesting that food cooling papers with LMIC affiliation are more likely to be linked to sustainability than those that only have authors from HICs and upper-middle-income countries.

As the literature has focused on HIC contexts, it has produced HIC-specific interpretations of what defines specific food cooling and SDG impacts. The conceptual bias toward considering food loss at the consumption level (Section 3.2) coincides with the fact that the majority of food loss occurs at consumption level in HICs (Hu et al., 2019). In LMICs, by comparison, 90% of food wastage occurs in the supply chain between farm and retail in LMICs (Heard & Miller, 2019; Ravishankar et al., 2020). In another example, almost all SDG7 hits relate to renewable energy usage in cold chains, while energy access and affordability of energy services made up only 3% and less than 1% of keywords, respectively. Yet for most of the LICs in the sample, affordable access to modern energy is a critical issue, and one that can be solved in certain contexts when designing business model innovations which combine it with generating revenue from decentralized food cooling in an integrated fashion (Trotter & Brophy, 2022).

This context imbalance in the literature is exacerbated by three factors. First, knowledge on how to design adequate cold chains is smallest where cold chain coverage is lowest (Heard & Miller, 2019). As country-level cold chain coverage rates are likely to be less than 5% in Ethiopia and Tanzania (FAO & IIR, 2016), there is a salient lack of adequate, context-specific business models, policies, and finance instruments to implement cold chains at scale in LMICs (Trotter, 2021). Second, the annual mean temperature is over 5°C higher in countries with fewer than 10 publications on food cooling compared to those with at least 10 such publications (Figure 6). Understudied countries are thus subject to higher per-unit cooling loads and hence, requiring more cold chain capacity per unit than well-studied industrialized countries. Third, especially West African, Sahelian, and several Southern Asia countries combine both high projected impacts of global warming and high projected population growth in the coming decades, disproportionally accelerating food cooling demand where knowledge gaps are greatest.

5 | AN AGENDA FOR SUSTAINABLE COLD CHAIN RESEARCH

With efforts to accelerate the global sustainability transition of food systems, research and interest in global food supply chains will increase in importance. We have argued here that food cold chains are key for achieving the sustainability transitions of the global food system, and can enable critical co-benefits across a large number of SDGs. However, our analyses suggest that the current literature linking cold chains with sustainable development, when evaluated on aggregate, exhibits knowledge gaps regarding the interconnectivity of goals (Section 4.1.2), the analytical depth across the supply chain (Section 4.2.2), and context specificity of cold chain designs especially in geographical areas with the highest needs for cold chain infrastructure (Section 4.3.2). We thus define a research agenda for sustainable food cooling to address these three gaps in turn.

5.1 | Consider sustainable development goals and their interconnections simultaneously when designing food cooling research

A large majority of food cooling research does not consider links to sustainable development. This is especially true for research published in food science-specific journals. However, as we have suggested in this paper, there are ample links between food cooling and sustainable development especially at the intersection of food, energy, transport, climate, and social systems (Khosla et al., 2020). There is thus a large

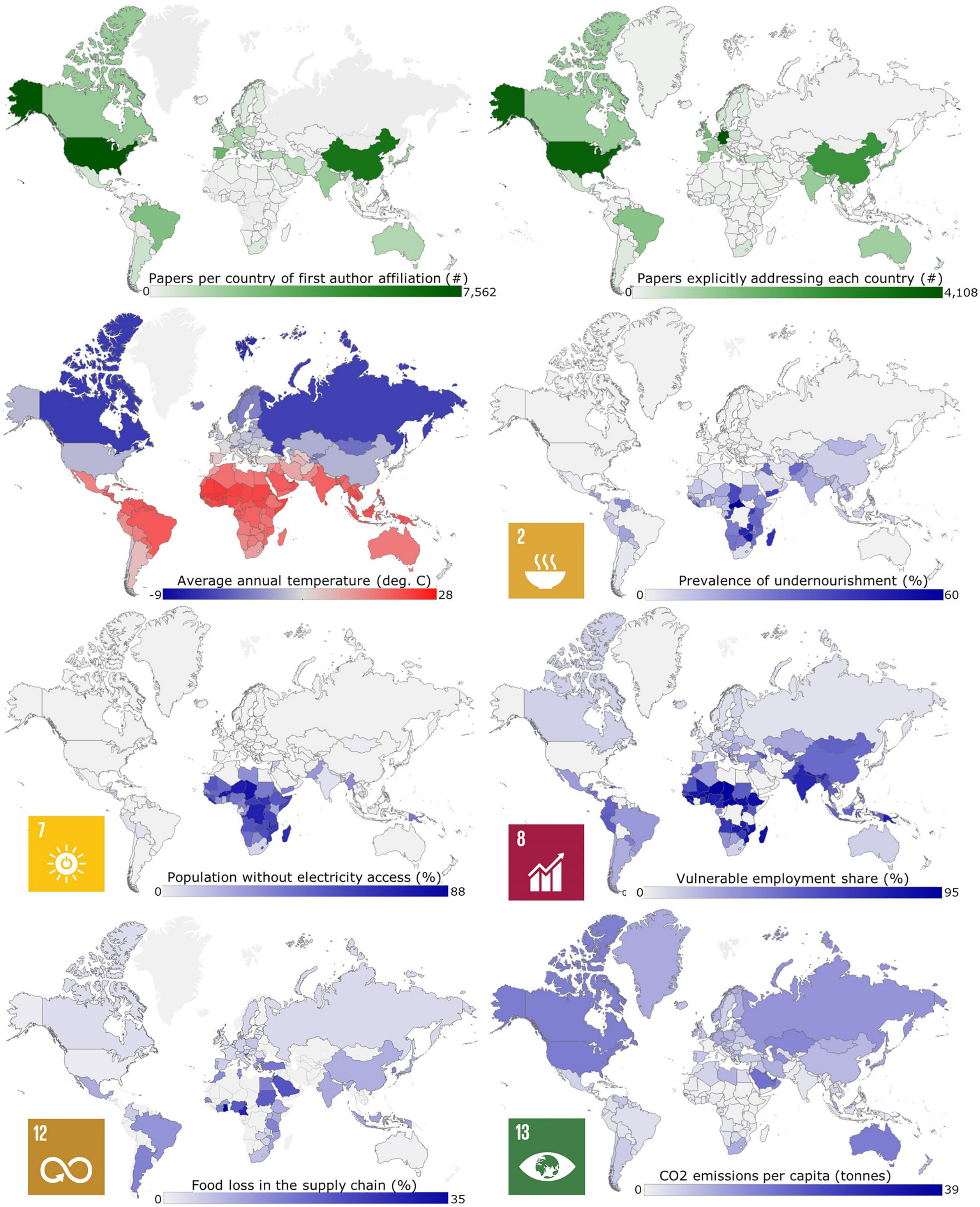

FIGURE 6 Geographical food cooling literature focus areas vis-à-vis annual mean ambient temperature and selected indicators for different Sustainable Development Goal progress. *Notes*: The upper two maps depict the geographical distribution of the food cooling literature identified in this paper. Data on food loss was sourced from The Economist Intelligence Unit (The Economist Intelligence Unit, 2018), all other data are from the World Bank (The World Bank, 2022). Countries are depicted in light grey where data were missing. All maps show the last year where data were available, all ranging between 2017 and 2019. While country-level cold chain coverage data are not available, the literature suggests that coverage is between 90% and 100% in leading high-income countries (Dong et al., 2021; Hu et al., 2019), while it is mostly stated to be less than 10% in most low-income countries (Dong et al., 2021; Hu et al., 2019), with recent estimates ranging between 4% for India (Birmingham Energy Institute, 2017) and 9% for Rwanda (UNEP & FAO, 2022). Underlying data for this figure are available in tab "data_from_figure_6" of the Excel file Supporting Information S5.

gap of studying food cooling as a lever for systems change toward sustainability which future research should address. While increasing the complexity of scientific analyses in the context of sustainable development does not automatically lead to better real-world outcomes (Schneidewind et al., 2016), evidence from organizational science and systems theory suggests that considering multiple goals simultaneously leads to better solutions and to improved impact on the ground than considering them in isolation or not at all (Lerner et al., 2014; Skene, 2021; Trotter & Brophy, 2022; Unsworth et al., 2014), especially where all goals are known to be important such as in the case of the UN's SDGs. Our analysis identifies three enablers that could help to address these gaps: First, given the predominance of siloed food cooling research, future research can analytically focus specifically on the opportunities for impacting sustainability transitions. There are several recent efforts by international development organizations to raise awareness of the potential of using cold chain designs in this way (Cool Coalition, 2021; FAO & WFP, 2020; Strahan, 2016; UNEP & FAO, 2022), all of which call for the need to more research on sustainable food cold chains.

Second, there is a need to for conceptual advances which unlock new fields of sustainable cold chain research, similar to what has been happening in the wider sustainability transitions field (Köhler et al., 2019). As fostering sustainability transitions is a systems issue (Willett et al., 2019), a critical component of intensifying research at the intersections of different SDG realms is conceptualizations that successfully bridge different disciplinary fields (Ahlborg et al., 2019; Häsler et al., 2019; Köhler et al., 2019). Our analyses suggests the potential of building on the growing work to embed food cooling research more closely in the water–energy–food nexus while also considering GHG emissions (Roibás et al., 2015; Zimmerman et al., 2018). For instance, combining a development studies lens with engineering approaches underscores the merit of pooling resources and constructing larger, centralized systems that make food cooling more accessible, have low GWP, and enable improved decision making regarding end-of-life considerations (Hart et al., 2020). Another example is defining cold chain design as part of wider energy and industrial systems to achieve symbiotic effects such as enhanced grid stability (Fikiin et al., 2017) and increased energy efficiency (Neusel & Hirzel, 2022).

Third, the interdisciplinarity of these conceptualizations of food supply chain research requires stronger academic collaborations across fields, echoing a call from the wider sustainable food transitions literature (Willett et al., 2019). This issue is particularly important for the food sciences which address links between food cooling and sustainability far less frequently than research from other disciplines. Collaborations for sustainability research are known to benefit from actively institutionalizing bridges between the critical fields involved (Bouzembrak et al., 2019). In the case of cold chains this would include (subsets of) food, agriculture, infrastructure, energy, transport, water as well as business and management sciences.

5.2 | Increase analytical depth by studying links between food cooling and sustainable development across the entire supply chain

Our results suggest that studying multiple food cooling supply chain stages simultaneously is associated with a deeper addressing of sustainable development. However, for several SDGs closely linked to food cooling, we find that there is a strong tendency toward analyzing only certain parts of the supply chain, creating thematic imbalances how these SDGs are linked with food cooling. Future research could define more integrated supply-chain-wide system boundaries for its analyses to counter this imbalance. Notably, our analyses suggest that depending on the SDG in focus, different parts of the supply chain appear to be underresearched despite known multi-facetted links to sustainability: For the goals of alleviating hunger (SDG2), water (SDG6), and energy poverty (SDG7), a stronger focus on the retail and consumer stages are required to study how food cold chains can increase affordable food, water, and energy access. Sporadic evidence suggests considerable potential of new integrated business models creating value across all these SDGs (Haney et al., 2019), but this research itself acknowledges the need for more in-depth analyses. For SDG12, by contrast, a majority of research discusses food waste at the retail and consumer stage, but there are limited analyses into how to effectively reduce food loss in the supply chain, both in HICs where systematic monitoring of temperature and humidity in the cold chain remains a key concern (Herrero et al., 2020), and in LMICs where low coverage is the most critical issue (UNEP & FAO, 2022). Crucially, adopting an integrated supply chain perspective to food cooling also allows to better identify synergies between SDGs. For instance, the expansion beyond traditional supply chain boundaries to including the GHG impact of food loss has allowed for holistic estimations of GHG emissions to decarbonize cold chains (Hu et al., 2019).

This holistic supply chain view implies the need for an added analytical emphasis on how the different actors along the supply chain can become agents of sustainability systems transition (Xue et al., 2021), and how new value networks for sustainable development can be formed between them (Trotter & Brophy, 2022). This includes farmers and agricultural companies as key adopters of innovative food cooling and monitoring equipment (Augustin et al., 2013; Kamble et al., 2020), cold storage chain companies as technological and cooling access innovators (Herrero et al., 2020), as well as retailers (Hamilton et al., 2014) and customers as food cooling demand managers and critical agents of lowering food waste (Madaki & Bavorova, 2019). The recent EU Farm to Fork policy is an example of a system-wide attempt at fostering sustainable food systems, however, the policy does not explicitly mention cooling or cold chains (European Commission, 2020).

5.3 | Focus on geographies and local contexts where sustainable food cooling knowledge gaps are most pressing

Our results suggest the importance of understanding context-specific sustainable development priorities to maximize the relevance of food cooling research for sustainable food transitions and the SDGs. In HICs, the high GHG emission of cold chains is a critical sustainability challenge (Ravishankar et al., 2020)—an area which remains understudied. As current and future anticipated types of GHG emission hotspots in cold chains are context dependent (Heard & Miller, 2016, 2019; Hu et al., 2019), more research efforts are required to identify case-specific decarbonization pathways that take into account demographic and urbanization dynamics as well as the existing food cooling infrastructure. In LMICs where SDG gaps are largest, we find evidence for multi-facetted synergies between food cooling and sustainable development relating to household income, food security, health, water, energy access, sustainable production, and conservation. Given the complexity of these links and the paucity of existing research, there is merit in a stronger empirical focus of future food cooling research on LMIC contexts to conceptualize and understand the food cooling and sustainable development nexus. Such research can be made actionable by identifying meaningful clusters of closely connected SDGs which lend themselves to being analyzed in an integrated fashion. An exemplary cluster is the nexus between food cooling, poverty reduction, food access, energy access, and climate action we find in our analysis. One of many potential ways of studying this cluster is through an integrated business model lens: Innovative servitization and sharing models use revenues from first-time provision of solar-energy-based food preservation to increase farmer incomes and cross-subsidize household energy access while limiting GWP impacts (Khosla et al., 2020). While such innovative approaches are able to deliver on a variety of SDGs simultaneously, they are inherently complex (Trotter & Brophy, 2022), and require a much better understanding of the underlying value capture mechanisms and partnerships needed to implement them at scale (Hirmer & Guthrie, 2017; UNEP & FAO, 2022). Finally, enabling such country-specific evidence in LMICs, especially when produced by LMIC researchers, is likely to require customized research finance schemes as well as adequate collaborative efforts (Mulugetta et al., 2022; Searchinger et al., 2019), recognizing the importance of diversity and positionality in authorship to produce meaningful, context-specific and relevant research (Mazzone et al., 2022).

A growing population, an income shift in emerging economies, and the global temperature rise are all critical drivers of food cooling demand. Given that lead times between generating scientific insights and seeing tangible actions on the ground can be long, there is an urgent need for a concerted effort to explicitly design food cold chains for sustainable development.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data generated from the large-scale text analyses which support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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