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Article

Not All E-commerce Emits Equally: Systematic Quantitative Review of Online and Store Purchases' Carbon Footprint

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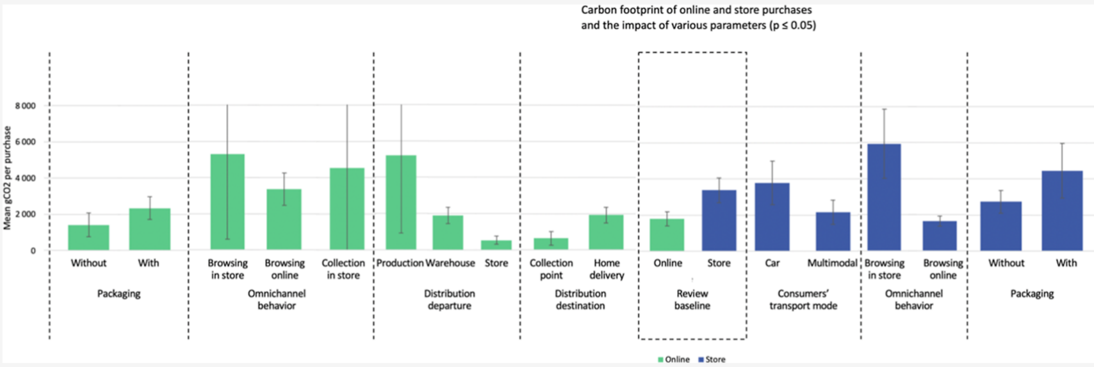

ABSTRACT: Although it has been studied extensively throughout the past 20 years, the environmental impact of e-commerce can still be considered a controversial subject. Particularly for those wondering whether online shopping constitutes a more environmentally friendly alternative to traditional store-based shopping, evidence can be found that quantitatively supports affirmative as well as opposing claims. Findings differ widely because the contexts and assumptions of the studies from which they are drawn differ widely as well. To advance our understanding of this question and inform actions that can actually reduce the environmental impact of shopping, we carried out a systematic quantitative review of environmental impact assessments that compares the carbon footprint of online and store purchases. Based on over twenty scientific studies, we compiled a dataset of 244 purchases, their estimated carbon footprint and information on the contextual, distribution, behavioral, and geographical conditions on which the calculations are based. We conclude from the reviewed studies that online purchases generally generate a lower carbon footprint than store purchases, but only in the case of car-dependent lifestyles, and possibly only because the studies largely overlook transformations in consumer behavior and in the consumption landscape.

KEYWORDS: *online shopping, online retail, home delivery, greenhouse gas emissions, environmental impact, sustainability, consumer behavior, consumption geography*

■ INTRODUCTION

After many years of incremental, double-digit growth in terms of turnover, it took a global pandemic imposing business closures and social isolation for the broad public to fully appreciate the vast purchase possibilities proposed by the worldwide web.[1] The availability of goods and services from computers and smartphones, together constituting the e-commerce sector,[2] is significant and expanding. Its prime position throughout the pandemic revived a debate that academics and practitioners have been fostering since its inception: on the environmental impact of e-commerce. The question whether it is more sustainable, or less, to shop online compared to shopping in stores is now well researched and well discussed. In essence, it comes down to the difference in processes required to distribute products from the place of production to the place of consumption, disregarding manufacturing, use, and disposal.[3]

Nonetheless, a common consensus lacks. What is more, vastly opposing answers find support among policymakers and practitioners alike, often depending on their specific perspective. This study aims to contribute nuance and clarity to the discussion by conducting a systematic quantitative review of comparative environmental assessments of shopping online and in stores. Studies on the environmental impact of e-commerce are important, as they shape public debate, shed light on the complexities, and ideally support appropriate policies to take shape.

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Several literature reviews have been carried out revising the knowledge to date.[4−12] Some date back nearly 2 decades and only two take a quantitative approach.[11,12] These studies are discussed in this section. Based on the findings of nine transport modeling assessments focused on groceries, Cairns concludes that the kilometers saved when shopping groceries online are likely to be substantial.[12] Assuming that delivery vehicles substitute car trips, she finds reductions of at least 70% with realistic levels of adoption (i.e., between 2.5 and 10%). In very stringent operating conditions or with very low levels of demand, savings of at least 50% are found. The article states that "the results are fairly simple and reflect that it is usually far more efficient for a few vehicles to make several round trips than for a large number of vehicles individually to travel to and from a store".[12] However, the study cautions as well that the complex behavioral responses by consumers could potentially bring about adverse effects.

Based on 11 studies assessing the energy efficiency of buying various products online or "offline", Pålsson et al. find a positive net effect for e-commerce in the majority of cases as well.[11] The authors focus on "search products", which are characterized by attributes that can be evaluated before the purchase takes place (e.g., books), as opposed to "experience products" that are evaluated when consumed or tested (e.g., clothing).[13] The study identifies five factors that determine whether e-commerce is more energy efficient than store-based shopping: the amount of unsold products and product returns; buildings, although only to a minor extent; packaging that contributes considerably especially in e-commerce; passenger transport; and freight transport.[11] The authors state that "the total energy consumption from transportation is greater in conventional supply chains, as the additional energy in passenger transport generally outweighed the increased energy in freight transport in e-commerce".[11]

Contrary to these studies,[11,12] most reviews take a conceptual approach in revising environmental impact assessments of online versus offline shopping. Abukhader and Jönson focus specifically on the range of methodological choices that influence impact assessments and their outcomes, including the type ("trade type") and the number of items bought ("product focus"), geographical area ("geographical borders"), type of market being business-to-consumer or business-to-business ("supply chain spectrums"), e-commerce penetration ("penetration into market"), included supply chain activities ("impact dimension"), and applied methodology ("tools/resource dimension").[4] They argue that most studies, regardless of their findings, find that e-commerce can generate both advantageous and damaging environmental effects.[4] In agreement, Mokhtarian states that impact assessments present "formidable measurement challenges" and calls for creative efforts to study e-commerce and its transportation impacts.[5]

Mangiaracina et al. explicitly concentrate on logistics processes, thereby following the dominant approach in the literature.[6] They identify four areas that affect e-commerce's environmental impact: transportation planning and management, warehousing, packaging, and distribution network design. The authors argue that each company operates in a specific context and caution that universal models do not exist.[6] However, logistic parameters are not the only ones to determine which way of shopping is more sustainable and define the environmental impact of e-commerce. Parameters on consumer behavior are equally, if not more, decisive. This is argued by Cullinane, who finds that the overall environmental impact of e-commerce is determined by "the net effect of substitution/complementarity, that is, after taking into account all the modification, generation, additional, and substitutional effects" that emerge among consumers.[7]

She considers how a new technology is used to conduct or change planned activities ("modification"); gives new information, new acquaintances, and new possibilities which induce more travel ("generation"); and comes in addition to old technologies ("addition").[7] Accordingly, the author goes beyond the "substitution bias", in which deliveries of online purchases are seen as directly replacing travel for in-store purchases. Similarly, Rotem-Mindali and Weltevreden attribute differences in study outcomes to disparities in defining "e-shopping" and "e-shopper".[8] At least two dimensions of the definition are important: whether searching and browsing activities, next to purchasing activities, are counted as e-shopping and the frequency with which e-shopping occurs.

Ultimately, parameters reflecting the geographical context and circumstances are also important. Feichtinger and Gronalt analyze scientific studies that assess the environmental impact of online and store shopping.[9] Highlighting the importance of study design, they list population density and population size among the factors to determine the environmental impact, next to basket sizes, consumption changes, delivery time windows, failed deliveries, general mobility effects, mobility modal split, interactions between channels, packaging, return rates, shopping frequencies, showrooming, trip chains, trips for other purposes, and unsold products.[9] The review of Buldeo Rai shares a similar objective and organizes all parameters to assess the net environmental impact of online versus offline shopping in three categories: "individual purchases" in which deliveries are considered substitutes for store travel, "consumer behavior" or e-commerce-induced behavioral transformations, and "consumption geography" or broader geographical developments that are pushed by e-commerce.[10] Taking 14 parameters into account, she argues that "when organized locally, efficiently, and consciously, e-commerce has the potential to be a sustainable alternative to in-store shopping".[10]

With a research base that has become increasingly nuanced and cautious not to promote one way of shopping over another, both overly optimistic[a] and unnecessarily dystopian[b] perspectives are still characterizing the public debate on e-commerce's environmental impact. Part of the debate's input is, however, driven with specific business interests in mind. Cited in ref,[7] the co-founder of online supermarket Ocado states that "each Ocado van replaces up to 20 cars on the road which overall can result in huge savings of unnecessary car journeys", while on the website of omnichannel supermarket Tesco, it is claimed that "each delivery van saves 6000 car journeys per year". Research reports funded by online retailer Amazon[14] and logistics real estate company Prologis[15] provide impact assessments that are positive as well about the impact of e-commerce on the environment. Yet, they omit some of the parameters that are considered necessary to include, particularly in most recent scientific research.

Research increasingly calls for acknowledging the variety of parameters that determine the environmental impact of e-commerce and the importance of specifying which parameters are (not) included.[8,9] In accordance, this study carries out a systematic quantitative review of environmental impact assessments that compare online and store shopping by means of carbon footprint calculations of online and store purchases. Based on the framework by Buldeo Rai, we compile

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Table 1. List of Parameters Investigated in the Systematic Quantitative Review

study source	study scope	distribution	purchase	consumer behavior	consumption geography
publication type	country	gCO_2	delivery failure	omnichannel purchases	store location
publication year	area type	distance	purchase return	fragmented purchases	warehouse location
	system boundaries	transport mode	basket size	purchase demand	mobility lifestyles
	product category	vehicle type	packaging	activity demand	
	product type	departure destination			
	purchase type				

a dataset to distill summary carbon footprints relative to various e-commerce scenarios and explore how they are impacted by different parameters.[10]

■ MATERIALS AND METHODS

Systematic Quantitative Review. Following the systematic quantitative review methodology proposed by Pickering and Byrne, this study aims to compile quantitative information on the carbon footprint of online and in-store purchases and determine the impact of various parameters.[16] There are hundreds of articles published using this method.[c] Although environmental impacts associated with various ways of shopping are diverse and include air pollution, noise nuisances, and infrastructural damages, among others,[17] this study concentrates on carbon dioxide (CO_2) emission equivalents. It is the most frequently used unit to convey environmental impacts in research on this subject. This study only considers the environmental impact generated by distribution but disregards the carbon emissions emitted through product manufacturing, use, and disposal. Although significant,[c] these activities remain unchanged whether a product is purchased online or in a store. Less decisive is energy consumption from using the Internet, lighting warehouses, and warming up stores, disregarded as well.

Using three scientific databases (i.e., Science direct, Scopus, and Google scholar) and 18 combinations of 23 keywords, we compiled a total of 21 articles on February 9, 2021. The keywords were selected to locate articles that empirically or theoretically compare (keyword "comparative") the environmental impact (keywords "environmental impact", "environmental sustainability", "carbon", "greenhouse gas", "CO_2", and "emissions") of shopping physical products online (keywords "e-commerce", "electronic commerce", "online retail", "online retailing", "electronic retail", "online shopping", "e-shopping", "home delivery", "omnichannel", and "omni-channel") and in stores (keywords "conventional", "traditional", "offline", "brick-and-mortar", "pickup", and "pick-up"). Despite an extensive list of references found in response to the keywords (4397), only peer-reviewed journal articles published in English after 2005 were included to guarantee the quality and relevance (458). Many of the articles appeared however in multiple searches.

Only 46 articles compare the environmental impact of online and offline shopping, 18 do so based on calculations of CO_2 emission equivalents. Therefore, we completed the total with four articles found through snowballing using articles' bibliographies. We added three conference articles and one Master thesis, all cited repeatedly and judged of equal quality in terms of literature underpinnings and methodological approach as the journal articles included. One article was excluded because of apparently distorted carbon footprints:[18] the values presented are several tens of times higher than others in our dataset, without clear explanation referring to the literature. In the end, it brought the total of articles included in the systematic quantitative review to 21. The article list is available in the Supporting Information of this article.

For each "purchase type" (i.e., online or store), we collected information on study source and scope, characteristics on purchase and distribution, and the generated amount of CO_2 emissions in grams (gCO_2) in a spreadsheet file (see Table 1). Within "system boundaries", we captured the supply chain's start and end that is considered in each calculation. While the former is either at production or at distribution, the latter constitutes either the point of purchase (i.e., stores) or the point of consumption (i.e., consumers' homes). "Area type" specifies whether a national, regional, or urban scope is considered in the studies. "Product category" indicates whether the considered product belongs to the food or non-food category, while "product type" designates it more precisely. For each purchase, we capture the distribution characteristics through parameters on travelled distance, transport mode (e.g., car and truck), and vehicle type (e.g., conventional and electric), as well as parameters specifying the start (i.e., "departure") and end point (i.e., "destination") to which distribution applies. Purchase characteristics contain parameters on delivery failure and return in percentages, basket size in number of items, and whether the environmental impact of packaging is considered.

Following the framework to assess the environmental impact of online shopping,[10] we also included whether studies incorporate ways in which e-commerce transforms consumer behavior and reorganizes consumption geography. Consumer behavior parameters recognize complex travel and purchase patterns that go beyond the assumption that deliveries of online purchases directly replace trips to stores. We consider "omnichannel purchases" (i.e., additional browsing or collection trips), "fragmented purchases" (i.e., one store trip replaced by several online purchases and deliveries), "purchase demand" (i.e., changes in total items bought), and "activity demand" (i.e., changes in total distance travelled). Consumption geography parameters incorporate transportation impacts of changing retail, logistics, and residential landscapes. We consider store locations, warehouse locations, and consumers' locations having an impact on their mobility lifestyles. Consult the article for more detailed explanations of the consumer behavior and consumption geography parameters.[10]

To build the spreadsheet file, two researchers completed the same half of the studies independently and compared inputs and optimized techniques accordingly. The first researcher drafted the spreadsheet file, which was optimized by the second researcher, who completed the remaining studies prior to final verification by the first researcher. The spreadsheet file is available upon request by contacting the corresponding author of this article.

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■ METHODS

From the 21 studies, 244 carbon footprint calculations originated. They are considered as separate assessments, as each calculation represents a different scenario and consists of different parameters. Our unit of analysis consists of one purchase, made online or in-store. One purchase can, however, consist of various items and translate in various trips. In some cases, various purchases can be consolidated in one trip. As we are interested in the difference in CO_2 emissions generated by two methods of purchasing, we follow the unit most consistently deployed in the literature, that is, purchases. We analyze the impact of each parameter on all assessments, by using the carbon footprint per purchase as a dependent variable and each parameter as an independent variable. We employed descriptive statistics and various statistical tests to identify which of the parameters significantly determine the carbon footprint of online and store purchases and in what way. Depending on the type of variable and the number of groups therein, we used the independent samples *t*-test, a one-way analysis of variance (ANOVA), and Pearson's correlation coefficient in the statistical software IBM SPSS Statistics. These statistical tests allow us to determine the differences between the means of independent groups.

Before each test, we verified whether the data violated the assumption of normality and of homogeneity of variances and whether it contained outliers, which was often the case. In case unequal variances were found using Levene's test, we ran the Welch *t*-test instead of the independent samples *t*-test and a Welch ANOVA instead of a one-way ANOVA,[19] which is recommended for unbalanced designs.[20] To graphically depict our findings, we plotted bar charts with error bars to generate 95% confidence intervals. We addressed the potential risk of bias by explicitly considering parameters employed in each study and thereby revealing underlying hypotheses. This applies both for bias assessment in individual studies and across studies throughout the created cumulative evidence.

■ MATERIALS

Of the 21 articles that constitute the basis for the review, 17 are journal articles published in Sustainability (3), Environmental Science & Technology (2), International Journal of Logistics Systems and Management (2), Transportation Research Part D (2), and other journals dedicated to environmental assessments,[d] transport and logistics,[e] and information technology,[f] contributing one article each. The conference articles are presented at the International Conference on City Logistics, Hamburg International Conference of Logistics, and the International Symposium on Sustainable Systems and Technology. Ultimately, the Master thesis is carried out at the MIT Center for Transportation & Logistics. Most articles are published recently (i.e., 3 in 2015, 2 in 2016, 1 in 2018, 4 in 2019, and 2 in 2020), with the oldest article dating back to 2008 and the oldest to 2020. The majority of studies concentrate on European countries, namely, Belgium (1), France, (1), Germany (1), Italy (3), Sweden (2), Switzerland (1), and the United Kingdom (3). Two articles concentrate on China, one on Jordan, and five on the United States.

All articles are empirical case studies and include environmental assessments of several different purchase situations. As such, they calculate the carbon footprint of online and store purchases in various scenarios, varying assumptions, and parameters. Listing every calculation, the database consists of 244 carbon footprints: 138 for online purchases and 106 for store purchases. While the journal articles contribute 86% of carbon footprint calculations, the conference articles represent 11% and the Master thesis 3%. Articles published in 2010 or before provide 14% of carbon footprints, articles published between 2011 and 2015 contribute 33%, and articles published in 2016 or later represent 53%. Consistent with the number of articles, the majority (63%) of carbon footprint calculations are relative to European cases, with Germany (11%), Italy (10%), Switzerland (12%), and the United Kingdom (20%) represented most. Carbon footprints from studies focused on China contribute 5%, Jordan 10%, and the United States 13%. For 10% of carbon footprints, no country of reference is identified.

The majority (81%) of calculations relate to non-food products, about one-fifth (19%) concern food products. Within the non-food category, clothing represents 47%, followed by electronics (12%) and books (6%). 4% of carbon footprints relate to an unspecified product type, while 31% concerns a variety of different products. Within the food category, 57% represents fast moving consumer goods, followed by groceries (23%) and meal kits (11%). A case study dedicated to the purchase of yoghurt specifically provides 9% of remaining carbon footprints in the food category.[21]

More than half (58%) of calculations take the so-called "last mile" perspective. Hence, they evaluate the environmental impact that is generated by distributing a purchase from a regional warehouse to consumers' homes, either directly in the case of online shopping or mediated by a store in the case of offline shopping, as Shahmohammadi et al. define.[22] Nabot and Omar specify that the last mile includes personal travel for store purchases or delivery vehicles delivering goods to customers for online purchases.[23] It is one of the most costly and polluting segments of the supply chain; oftentimes, it is also the most energy-demanding.[11] In this analysis, last mile assessments assume storage of products in proximity to where they are consumed. For example, two articles present cases on omnichannel retailers that rely on local warehouses to support both their webshop and store activities.[24,25]

This last mile perspective acknowledges that consumer products are produced remotely, in most cases, but assumes that local warehouses are supplied efficiently, regardless of whether the products are sold online or offline.[26] It does, however, not cater adequately to the development and dominance of international marketplaces that rely heavily on remote warehouses to ship online purchases individually, through means that are less efficient but fast, such as airfreight. Through this combination of individually packaged items and polluting transport modes, the total energy consumption of e-commerce skyrockets. The last mile perspective also does not take surging cross-border e-commerce into consideration, implying considerable lengthening of overall distances. Less than half of calculations (41%) start off from the place of production. The study on meal kits provides one example.[27] They thus follow a lifecycle perspective in parts.[28] The lifecycle perspective is more prevalent when it comes to food (92%) compared to non-food (28%).

Only for a minority of carbon footprint calculations, the distribution distance is specified: for 33% of calculations when it comes to the roundtrip distance and only for 14% of calculations when it comes to distance per purchase. The latter is calculated based on the total number of deliveries per roundtrip for online purchases[29] and the total number of

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activities per roundtrip for store purchases (i.e., "trip chaining").[23] Accordingly, online purchases generate an average of 19 km travelled for distribution, while store purchases generate an average of 37 km travelled. When it comes to transport mode and vehicle types, specifications lack for, respectively, 23 and 37% of calculations. Vans are most common for online purchases (65%) and cars for store purchases (53%). Multimodality is common as well for consumers' travel to stores (29%). Articles then aggregate the environmental impact associated with different transport mode uses, representative for the considered population.[22,25,30] For both online and store shopping, conventional vehicle types represent the vast majority, to the detriment of electric or other alternatives.

Most (83%) carbon footprint calculations do not take delivery failure into consideration. It is a risk that only applies when purchases are delivered, instead of collecting in collect points or stores.[31] When considered, an average failure rate of 21% is applied, with a maximum of 50% of deliveries that are assumed to fail. Contrary to delivery failures, a risk of return where consumers do not want their purchase anymore exists for both online and store purchases,[32] albeit higher in the former (for 59% of carbon footprints) than the latter (for 26% of carbon footprints). When a return percentage is considered, an average of 27% is applied for online purchases, with a maximum of 100%, while an average of 8% is applied for store purchases, with a maximum of 30%. An average online shopping basket contains 11 items when purchased online, next to an average of 12 items when purchased offline. In terms of product categories, basket sizes in food have an average of 24 items, contrary to an average of eight items in non-food.

The impact of packaging is considered in 59% of carbon footprint calculations for online purchases and in 46% of carbon footprint calculations for store purchases. How packaging contributes to the environmental impact of purchases is studied in detail by Zhang and Zhang, among others.[33] Half of the carbon footprint calculations are focused on the country level (51%), while the remainder is split between regional (21%) and urban (28%) level assessments. This division is fairly similar when split between online and store purchases. Wygonik and Goodchild demonstrate that the relative density of areas can explain about half of the variation in CO_2 emissions among consumers delivered at home.[34] They find that population density and urban form influence the degree to which CO_2 emissions are reduced but conclude that reductions are to be expected in all area types if delivery trucks are filled to capacity and routing and scheduling strategies are efficient.

Except for omnichannel purchases, calculations hardly consider the impact of changes in consumer behavior and consumption geography on the carbon footprint of purchases, either online or in-store. Omnichannel purchases are considered in 20% of carbon footprint calculations: online researching (12%) or research in stores (4%) prior to an online purchase and online researching (3%) or researching in stores (16%) prior to an offline purchase. Browsing-only shopping trips are considered in two cases.[3,35] Their occurrence represents one of the parameters constituting the consumer profiles in two other studies.[36,37] In 4% of carbon footprint calculations for online purchases, store travel is implied for accessing the purchase (i.e., "click and collect"), while a delivery is implied after the purchase in 1% of carbon footprint calculations for store purchases. Two studies propose such scenarios, for example.[25,38]

The impact of fragmentation of purchases on carbon footprint calculations is considered in only 14%, despite growing acknowledgement for its importance in various studies. Siragusa, Mangiaracina, and Tumino, for example, consider in their calculations that consumers often buy multiple items during one shopping trip, which typically translates into different shipments from specialized retailers when shopping online.[39] Changes in purchase demand, thus implying more purchases, deliveries, and travel, are considered in 2%, and changes in activity demand, thus implying more travel, are considered in 2% as well. Even less consideration is made to changes in consumption geography: 1% of carbon footprints consider changes in store locations, 2% reflect changes in warehouse locations, and none of the articles explore changes in consumers' mobility lifestyles. Environmental implications are, however, likely. Finally, instead of pushing consumers' demand for goods and travel, e-commerce can also reduce consumers' need for cars and discourages car dependence. Although the impact assessments published in the literature only consider the behavioral and geographical changes induced by e-commerce to a limited extent, the next section further explores their impact on purchases' carbon footprint when they are, as well as that of the other parameters, discussed.

Findings. *Carbon Footprints of Online Purchases Compared to Store Purchases.* As the bar chart in Figure 1 shows, the carbon footprint of online purchases in our study tends to be lower than the carbon footprint of purchases carried out in-store. Based on the compiled dataset, an online purchase produces a mean of 1810 gCO_2, while a store purchase accounts for a mean of 3395 gCO_2 ($p < 0.001$). The research converges more on the carbon footprint of online purchases than that of store purchases. Online purchases range from about 300 gCO_2 in the 25th percentile to about 2400 gCO_2 in the 75th percentile, while store purchases vary between a carbon footprint of about 1000 gCO_2 in the 25th percentile (i.e., more than threefold) to 4600 gCO_2 in the 75th percentile (i.e., double). It indicates that the way store purchases are organized differs more widely than operations behind online purchases. Indeed, store purchases are an immediate result of consumers' purchase and travel behavioral patterns that can be diverse, while online purchases are almost completely operated by companies functioning on business

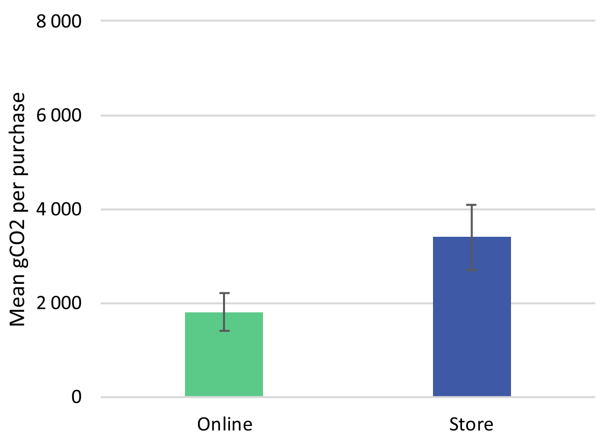

Figure 1. Carbon footprint of online and store purchases.

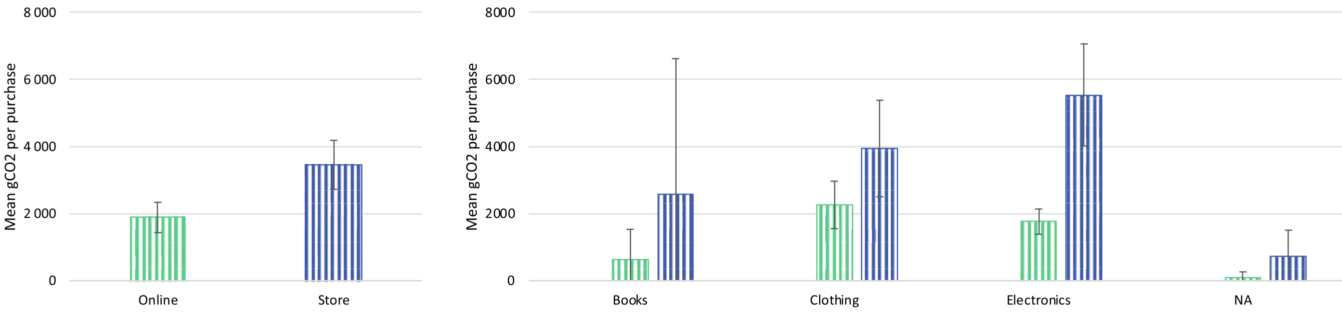

Figure 2. Carbon footprint of online and store non-food purchases (left) split into product type (right).

rationales that are more similar. Throughout this section, a common layout for figures is applied: green bars represent online purchases, blue bars represent store purchases, dashed bars represent non-food purchases, and dotted bars represent food purchases.

We established a statistically significant difference between online and store purchases for non-food purchases specifically ($p < 0.001$), with an average carbon footprint of 1886 gCO_2 for online purchases and of 3448 gCO_2 for store purchases. For food purchases, variations among carbon footprints are too vast for store purchases to generate statistically significant differences compared to online purchases ($p = 0.176$). Figure 2 illustrates the statistically significant findings for non-food purchases. They motivate further exploration into product types. Figure 2 also illustrates the selection of non-food product types of which online and store purchases' carbon footprints differ statistically significantly: books bought online generate an average carbon footprint of 630 gCO_2 compared to 2580 gCO_2 in-store ($p = 0.041$), clothing bought online generates an average carbon footprint of 2261 gCO_2, compared to 3947 gCO_2 in-store ($p = 0.038$), electronics bought online generate an average carbon footprint of 1769 gCO_2, compared to 5534 gCO_2 in-store ($p < 0.001$), and the category of unspecified products bought online generates an average carbon footprint of 103 gCO_2, compared to 738 gCO_2 in-store ($p = 0.041$).

The next paragraphs explore the impact of various parameters on the carbon footprint of online purchases, compared to that of store purchases.

Impact of Transport Modes and Vehicle Types. A comparison between carbon footprint calculations assuming car travel (53% of calculations) and other transport modes (30% of calculations) demonstrates a higher average impact for the former (3784 gCO_2) and a lower impact for the latter (2147 gCO_2), see Figure 3. In this way, the review provides a carbon footprint of store purchases that is similar to that of online purchases, when assuming a consumer base that walks, bikes, or takes public transportation (i.e., is multimodal) instead of being car dependent. This difference is statistically significant ($p = 0.019$). It highlights the importance of consumer mobility, although we did not have sufficient data to calculate the impact of each sustainable travel scenario separately. In case of online purchases, the majority (65%) of calculations assume deliveries by van, impeding more detailed analysis as well. When it comes to vehicle types alternative to conventional fuels (diesel mostly), carbon footprints are clearly lower for both online and store purchases, although calculations are too limited to provide significant statistics.

Impact of Area Types, System Boundaries, and Distribution Departures, Destinations, and Distances. We considered whether studies applied a national, regional, or urban scope. Carbon footprints decreased from urban (2903 gCO_2), over regional (1860 gCO_2), to national contexts (1135 gCO_2) for online purchases (Figure 4), a difference found statistically significantly ($p = 0.002$). We observed a similar pattern for store purchases: 5155 gCO_2 for urban contexts, 5025 for regional contexts, and 1901 for national contexts (Figure 4), found statistically significantly as well ($p < 0.001$). Studies with an urban scope thus produce generally higher average carbon footprints for purchases in our study, while those with a national scope produce the lower ones. These findings reflect the bias in the literature in favor of motorized transport, for both consumers shopping and companies delivering. Because of densities and inefficiencies in urban areas, transport externalities affect larger populations and are potentially higher as well.[39] We did not come to significant nor straightforward conclusions on studies' case study country or system boundaries and the carbon footprint of purchases.

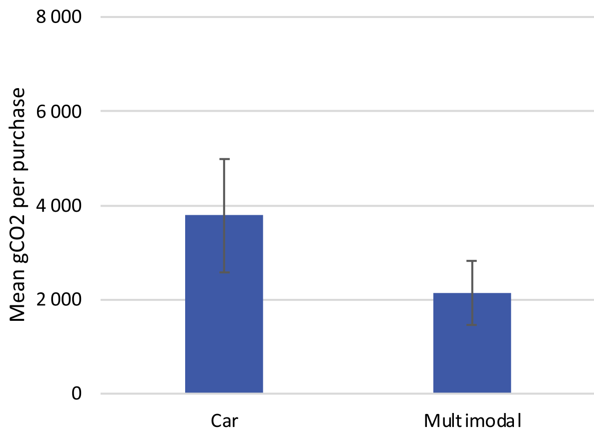

Figure 3. Carbon footprint of store purchases split into modal choice.

When it comes to final distribution of purchases, the average carbon footprint for online purchases decreases when organized closer to consumers: 5200 gCO_2 from the place of production (although only relevant for meal kits), 1003 gCO_2 from the warehouse, and 551 gCO_2 from the store for food purchases; 2060 gCO_2 from the warehouse; and 523 gCO_2 from the store for non-food purchases. Figure 5 visualizes the statistically significant findings separately for food ($p < 0.001$) and non-food ($p < 0.001$) purchases. It confirms the importance of consolidated and bulk forms of goods transport, when supplying warehouses and stores, in contrast to more individualized forms of transport, when making deliveries. The analysis cannot be extended to store purchases: if production or warehouse sites are listed as departure locations instead of stores, it signals an omnichannel behavior in most cases (e.g.,

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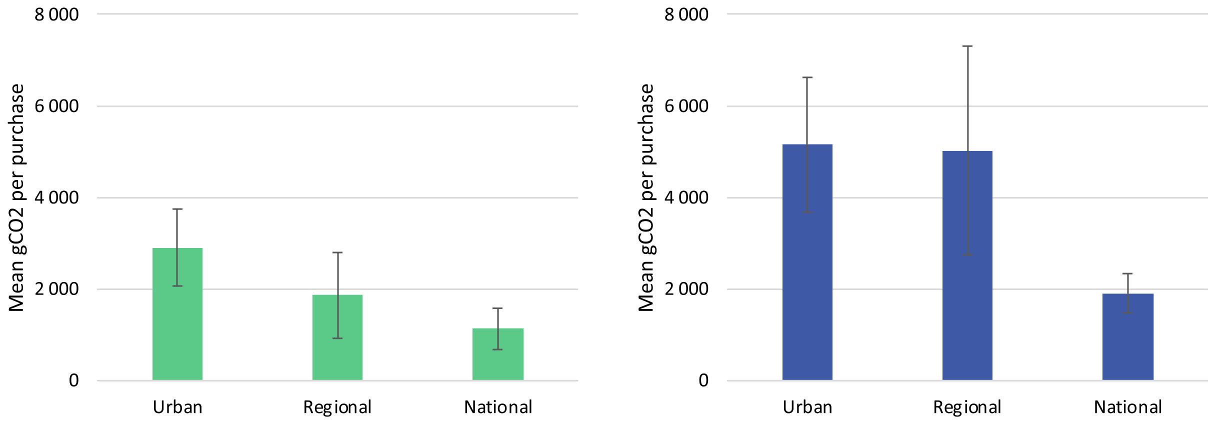

Figure 4. Carbon footprint of online (left) and store (right) purchases split into area type.

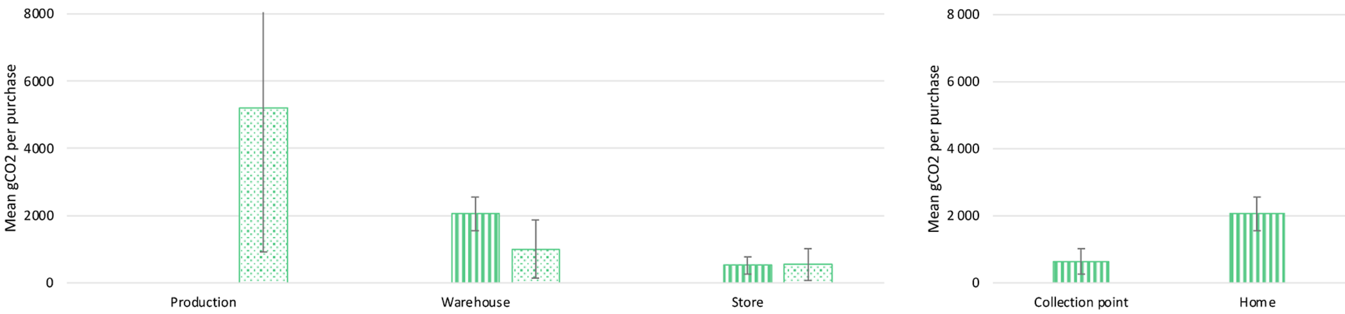

Figure 5. Carbon footprint of online food and non-food purchases split into distribution departure (left) and distribution destination (right). Impact of basket size, delivery failure, purchase return, and packaging.

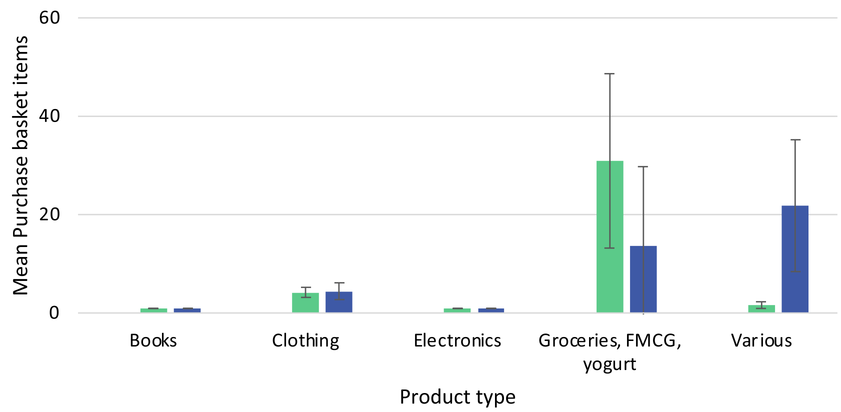

Figure 6. Basket size of online and store purchases split into product type.

in which store purchases are not immediately collected by consumers but instead delivered at home).

For online purchases, a statistically significant difference in average carbon footprint is found as well when it comes to destinations of distribution, that is, either at collection points or at home. While home deliveries of online non-food purchases amount to an average carbon footprint of 2060 gCO_2 in our study, collection point deliveries only generate 641 gCO_2 (Figure 5), a statistically significant difference ($p < 0.001$). Here as well, underlying assumptions are important, as collection point deliveries imply collection trips by consumers. These are not always considered and can considerably undermine collection points' environmental advantage.[25] In the literature, collection points are not considered for food purchases. In both online and offline shopping scenarios, we did not find clear or significant relations either between distances covered per purchase for final distribution and carbon footprints, possibly as well because of insufficient calculations.

When it comes to the number of items purchased at once, there is a difference between product types in the case studies included in our review: books and electronics are considered "unique" purchases, while clothing (4 on average) and groceries and fast moving consumer goods (24 on average) are assumed to be purchased in larger numbers. While studies consider larger baskets in-store than online for non-food purchases (an average of 11 items in-store compared to 3 online), they assume the opposite for food purchases (an average 14 items in-store compared to 31 online) (Figure 6). Assumptions on basket size are important. Lower CO_2 impacts seem to be generated per purchase for bigger baskets and

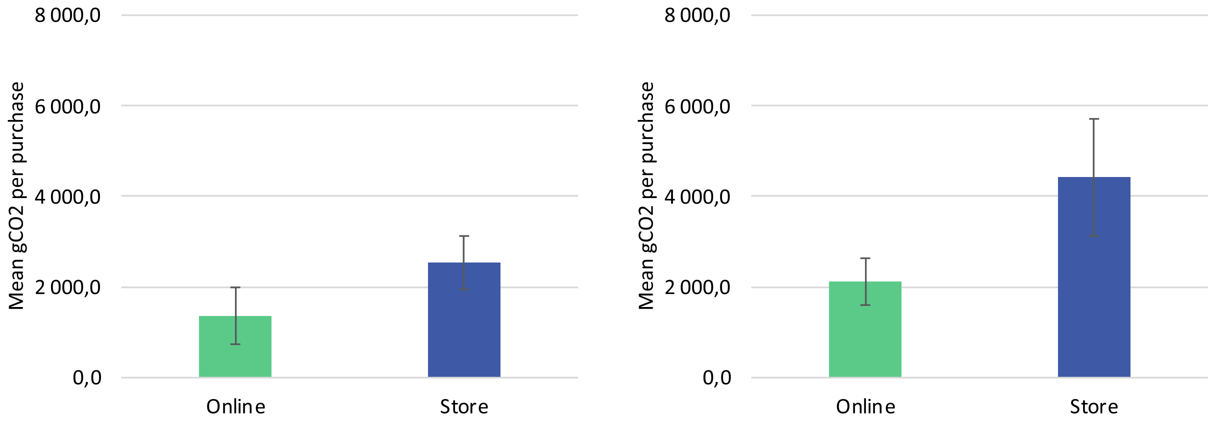

Figure 7. Carbon footprint of online and store purchases split into packaging not considered (left) and considered (right).

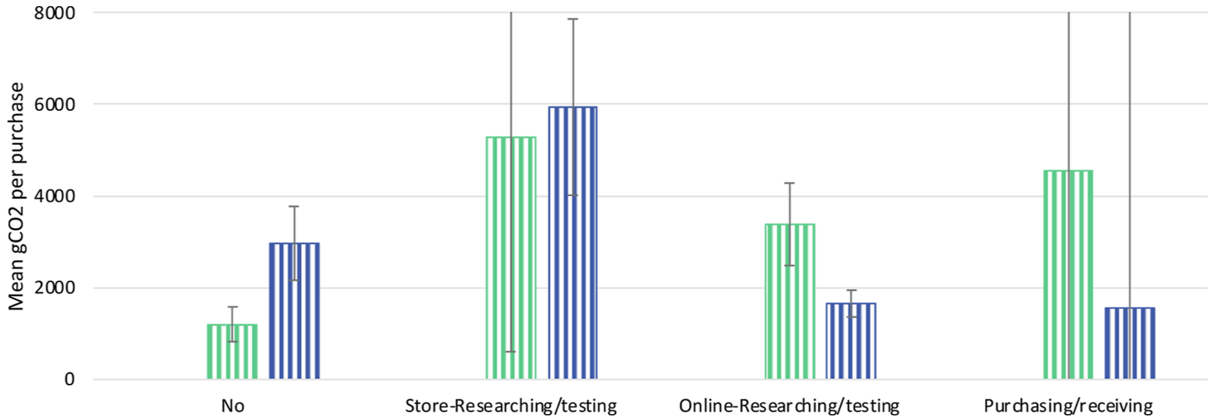

Figure 8. Carbon footprint of online and store non-food purchases split into omnichannel purchase type.

higher impacts per purchase for smaller baskets, although we cannot demonstrate statistical significance to support this.

Delivery failures (17% for online purchases in this review) and purchase returns (60% for online and 25% for store purchases in this review) are considered in few calculations. Their impact on carbon footprints is not straightforward. When it comes to delivery failures, the average carbon footprint of online purchases is actually a lot lower when it is taken into account, as compared to when it is not. This finding is unrealistic as failure during home delivery always implies additional vehicle kilometers, either by delivery companies following redelivery to another place (often a collection point) or redelivery to the same place but on another point in time (often the next day) or by consumers following collection trips to collection points. Beyond data insufficiencies, it is possible that delivery failure rates are less significant in e-commerce carbon footprint calculations.

When it comes to purchase returns, we come to similar conclusions. The average carbon footprints for both online and store purchases are lower when returns are considered, compared to when they are not, despite the findings in the literature that returns more than double e-commerce's environmental impact.[32] However, dividing online purchases in the various product types, we find that carbon footprints that do take returns into consideration are higher than those that do not. This is the case specifically for books, electronics, groceries and fast moving consumer goods, and baskets of various items. Although these findings are more in line with the literature, we cannot demonstrate statistical significance. A closer look to clothing, where returns seem to lower the carbon footprint, indicates the shortcomings of a dataset compiled of case studies. Clothing is researched most in the literature and thus more than any other product type considered, pools data from diverse studies. It is a possible explanation for this error. When it comes to purchase returns and delivery failures, the dataset on both parameters is probably insufficient and remains therefore inconclusive.

The impact of packaging is considered highly important: two studies even refer to this parameter in their article titles.[11,40] The share of calculations that take packaging into account confirms this as well: 59% for online and 46% for store purchases. Carbon footprints that do not take packaging into account are lower (1952 gCO_2) compared to the ones that do (2990 gCO_2). This difference is statistically significant (p = 0.006). The difference is clear for non-food products (2079 gCO_2 compared to 3224 gCO_2, $p = 0.010$) but is especially striking for food products (about 270 gCO_2 compared to about 2444 gCO_2, $p < 0.001$). These differences are statistically significant as well. Figure 7 illustrates the findings.

Impact of Consumer Behavior. About one-fifth of carbon footprint calculations take some kind of omnichannel consumer behavior into consideration, in which the impact of combined channel use for a single purchase is estimated: for 19% of online purchases and 21% of store purchases, albeit for non-food purchases only. The difference is statistically significant for non-food purchases online ($p = 0.006$) and offline ($p = 0.009$), see Figure 8. Online browsing prior to an online non-food purchase results in a carbon footprint of 3,376

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gCO_2, which is higher than the overall average carbon footprint of 1886 gCO_2 and higher as well than the average carbon footprint of 1,200 gCO_2 originating from studies that do not consider omnichannel consumer behavior. This finding suggests that online purchases' carbon footprint grows as consumers become more invested, even if through online channels only. It possibly leads to more remote (i.e., increasing distance) or specialized purchases (i.e., increasing inefficiency). Online non-food purchases' carbon footprints increase when an online transaction is followed by store collection requiring travel (i.e., "click-and-collect"), with an average of 4545 gCO_2. It increases as well when consumers travel to stores prior to the online purchase for browsing (i.e., "showrooming"), with an average of 5287 gCO_2.

Differences in carbon footprint are statistically significant as well for store non-food purchases ($p = 0.009$), see Figure 8. Online browsing prior to a non-food store purchase, or "webrooming", leads to a carbon footprint of 1650 gCO_2, which is considerably lower than the overall average of 3448 gCO_2, as well as lower than the average of 2969 gCO_2 originating from studies that do not consider omnichannel consumer behavior. This finding brings evidence for the optimizing effect that e-commerce can have on store travel, providing practical information on opening hours and stock availabilities of stores, for example. Similar to online purchases, carbon footprints of store purchases increase when consumers engage in additional store travel prior to the purchase (5934 gCO_2), while in-store purchases delivered at home, requiring a professional and a consumer trip for the same purchase, imply only 1550 gCO_2, which seems strangely low. Perhaps, this type of omnichannel behavior is considered only when consumers walk or bike to stores and therefore benefit from local delivery services, both of which reducing the environmental impact. The dataset does however not provide sufficient details to support the hypothesis.

About a fifth of calculations consider the impact of fragmentation on online purchases' carbon footprint, that is, the concept that they do not replace store visits fully, but only in parts. For example, van Loon et al. include 75 or 90% of consumer travel to stores on top of the e-commerce emissions, depending on the fulfilment method.[30] When considered, fragmentation increases the carbon footprint on online purchases: for non-food, with an average carbon footprint of 4563 gCO_2 for a fragmented online purchase, compared to 1754 gCO_2 when fragmentation is not considered; and for food, with an average carbon footprint of 1596 gCO_2 for a fragmented online purchase, compared to 1351 gCO_2 when fragmentation is not considered. For the remaining parameters reflecting on consumer behavior (i.e., purchase and activity demand) and consumption geography (i.e., store locations, warehouse locations, and mobility lifestyles), data were insufficient to perform further analysis.

DISCUSSION

Based on the studies included in this systematic quantitative review, we find that online purchases produce a mean of 1810 gCO_2, while store purchases account for a mean of 3395 gCO_2. The CO_2 impact ranges from 300 gCO_2 to 2400 gCO_2 for online purchases and from 1000 gCO_2 to 4600 gCO_2 for store purchases. These findings allow to establish a sort of maturity in this field of research. We can draw several conclusions from this review, which in the first place relate to the ever so relevant and pressing question, on whether it is more environmentally sustainable to purchase our items online, as these numbers suggest. In the second place, this systematic quantitative review presents ample opportunities for future research on this continuously evolving subject, which we address as well.

When it comes to the environmental impact of e-commerce, which is investigated in this research by focusing specifically on CO_2 emissions or carbon footprint, it appears important to distinguish explicitly among various types of "online shopping". Although a fairly obvious point, it tends to get lost in research and especially in public discussions: the impact of e-commerce is considered homogeneous, while e-commerce is in fact heterogeneous, encompassing diverse business models with diverging impacts. On the most basic level, the distinction between shopping for food and non-food products sold through online channels is essential. Consumer behavior differs quite considerably in parameters that influence the environmental impact of e-commerce: basket sizes (higher for food), delivery failures (higher for non-food), purchase returns (higher for non-food), omnichannel purchases (only examined for non-food), and fragmented purchases (determined mostly for non-food). Our dataset allows us to demonstrate the impact of two specific behavior types: online browsing prior to a store purchase or "webrooming" and store browsing prior to an online purchase or "showrooming". While webrooming seems to reduce the carbon footprint of a store purchase (from 3448 gCO_2 to 1650 gCO_2), showrooming seems to have the opposite effect for online purchases (from 1886 gCO_2 to 5287 gCO_2).

The online supply chain is organized quite differently as well. For example, last mile distribution of food items to consumers can be organized from the place of production (e.g., local produce), but this is very uncommon for non-food items. Similarly, extensive packaging is more important and common for food, compared to non-food. The research specifically points to clothing and electronics as two product types that are mobility-heavy and generate numerous travel behaviors (e.g., prone to returns and browsing trips). Some increasingly common types of e-commerce are absent in research, particularly in the food sector, e.g., groceries click-and-collect, local food chains, and groceries delivered within minutes (i.e., "quick commerce"). They deserve comprehensive investigation, with particular attention to the behavioral and geographical transformations that they potentially generate.

This research confirms the determining impact of the proverbial "last mile" on the environmental impact of e-commerce and highlights the importance of local infrastructure from which distribution rounds depart, that is, local warehouses and stores. What is more, such infrastructures enable to use low-impact transport modes (e.g., cargo bikes) and vehicle types (e.g., electric vans), creating possibilities for e-commerce to reduce its impacts. This research supports the environmental potential of alternative transport modes and vehicle types for e-commerce, although more studies and data are required. Yet, the most environmentally friendly e-commerce business models require the population density and tech-forwardness of urban environments to be feasible and viable. Dense cities, paradoxically, are also where consumers' mobility lifestyles are most sustainable and thus have an environmental impact that is already low. Including for shopping, levels of walking, cycling, and public transportation are highest in cities, making them least favorable to be replaced (or complemented) by e-commerce from an environmental point of view. On the contrary, e-commerce performs consistently better when

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compared to car-based store visits, which this research demonstrates as well. As such, the environmental advantage of e-commerce is most promising in suburban areas, where car dependence is strong but density remains sufficient for deliveries to be efficient.

Using our systematic quantitative review, we have identified data insufficiencies and inconsistencies across studies. For future research, we first recommend to be more explicit about underlying assumptions and parameters, both in a descriptive and quantitative sense. As the literature base on this subject exists for the most part out of highly contextual case studies, carefully described and quantified research conditions allow comparisons and facilitate understanding. Second, we propose a more comprehensive approach to the types of parameters that are included to compare the environmental impact of online and store purchases. In particular, behavioral (i.e., consumption as well as travel) and geographical conditions of today's retail system are generally missing from the studies. For example, important online retailers do not necessarily rely on local warehouses when selling and delivering online purchased items. Cross-border e-commerce in particular has no warehousing presence in export countries. This is largely neglected by research. Contrarily, the new "quick commerce" business model relies on mini-warehouses located centrally in cities, with supply structures that are not investigated yet. Importantly, the impact of returns on e-commerce's carbon footprint merits more investigation. Third, exploring and understanding behavioral and geographical implications become even more important in the future, as emerging e-commerce business models mature, such as the ones that rely on anticipatory shipping (i.e., a system of delivering products to consumers before the order is placed), ones that propose automatic subscriptions generating a very high frequency of deliveries, and ones that offer instant deliveries as a way of "outsourcing your fridge"..

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00299.

List of 21 studies analyzed in a systematic quantitative review (PDF)

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Notes

The authors declare no competing financial interest.

ADDITIONAL NOTES

[a]"Jeff Bezos says ordering groceries online is better for the planet. Is he right?", https://grist.org/food/amazon-jeff-bezos-says-ordering-groceries-online-is-better-for-the-planet-is-he-right/.

[b]"We need to have a difficult conversation about online shopping and the environment", https://www.independent.co.uk/independentpremium/voices/amazon-prime-day-shopping-climate-b1870679.html.

[c]A full list of them is available from Google Scholar: https://scholar.google.com.au/scholar?cites=14884161913286735942&as_sdt=2005&sciodt=0,5&hl=en.

[d]That is, International Journal of Life Cycle Assessment; Journal of Cleaner Production; Journal of Industrial Ecology; Resources, Conservation & Recycling; and Science of the Total Environment.

[e]That is, International Journal of Physical Distribution & Logistics Management and Journal of the Transportation Research Forum.

[f]That is, International Journal of Computer Applications.

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