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A systematic scoping review of environmental, food security and health impacts of food system plastics

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Plastic pollution arising from food systems is driving policies for reduction, removal, reuse and recycling, but literature on plastic uses and outcomes across subsectors is fragmented. We use a systematic scoping review to describe the extent, range and nature of published evidence since 2000 on seven major plastic types used at any point within food systems and their quantifiable effects on the environment, food security and human health. Although the majority of publications focus on agricultural production, relatively fewer consider retail, household and food waste disposal plastics. Gaps in the research include evidence from low- and middle-income countries, health or food security and/or economic outcomes generated from human population studies—and the subsequent environmental and human health effects. A greater understanding of this disparate evidence landscape is essential to formulate coherent research strategies to inform potential policy actions and assess trade-offs across economic and environmental targets, human health and food security.

Over 8.3 billion metric tonnes of plastics have been produced since the 1950s and proliferation in their use has been exponential[1]. The agricultural sector uses 6.5 million tons of plastic film mulch annually[2]; food and drink packaging alone accounts for around 16% of the total plastic production over the past 70 years[3]. Single-use plastics continue to expand across food systems globally—although circular economy policies seek to reduce their source, repurpose their waste and halt their pollution, such strategies are likely to have consequences across wider sectors with overlapping implications for health, the environment, food security and economic outcomes. Scientific evidence on these broader effects of food system plastics is rapidly growing, but it remains fragmented across disciplines and impact domains.

Plastics are low-cost, versatile, lightweight and durable[4]. Plastic food packaging acts as a barrier to contamination[5], and supports household economics and food security by minimizing post-harvest losses, extending shelf-life and storage capacity[5], and agricultural plastics can reduce chemical fumigant use in farming as well as transportation fuel consumption[6,7]. However, global food waste has increased alongside plastic packaging use[3]. Macro-, micro- and nanoplastics have been detected in Arctic snow, mountain air and the tissue of marine species[8–10]. The accumulation of microplastics in food chains and leaching of harmful substances, such as bisphenols and phthalates, into food and drink products is of increasing concern—although their potential health effects remain unclear[11,12].

To support evidence-based policy actions and inform evaluations of potential trade-offs, the extent, range and nature of evidence from disciplines across food system sectors need to be systematically synthesized. Here we use a systematic scoping review of plastics in the food system to describe the research landscape, highlight gaps, generate new research questions and identify mature evidence. The approach taken here minimizes selection bias and ensures that evidence maps are comprehensive across different disciplines, which include materials sciences, public health, agricultural sciences, food technology, nutrition, economics and environmental sciences. We developed an interactive open-access evidence map that describes the extent (volume of research), range (variety of exposure–outcome relationships) and nature (study characteristics) of quantifiable evidence on the effects of food system plastics, in which exposure to any of the seven categories of common plastics used within any stage of the food system, in relation to theorized intermediate and final outcomes relevant to the domains of Human Health, household food security and/or economics (Food Security/Economics) and the natural environment (Environment) can be viewed (Fig. 1, Box 1 and Methods)[13–15].

Results

We returned 49,850 unique results (excluding duplicates), of which 3,362 records were included for analysis in our review (Fig. 2 and the interactive evidence map available at https://anh-academy.org/foodplastics_EGM.html).

Extent of the evidence. Publications per year more than quadrupled from 2000 to 2018, with a similar volume of studies in middle-income countries (MICs) (50.1%) and high-income countries (HICs) (48.3%), but little evidence from low-income countries (LICs) (1.6%) where plastic usage is rapidly growing. China, the United States of America, India, Italy and Spain contributed to almost half of the evidence in our review. Most studies explored plastics used in Agricultural Production, followed by Processing, Storage and Distribution, but only four considered those used in Waste Disposal (Fig. 3a). Plastic types were commonly unspecified or polyethylene (PE) ($n=1,137$ and 1,209 studies, respectively), followed by polypropylene (PP) ($n=574$), low-density polyethylene (LDPE) ($n=453$), miscellaneous plastics ($n=423$) (Box 1), polyethylene terephthalate (PET) ($n=319$), high-density polyethylene (HDPE) ($n=214$), polyvinyl chloride (PVC) ($n=192$) and polystyrene, styrene or Styrofoam (PS) ($n=157$ studies, <5%).

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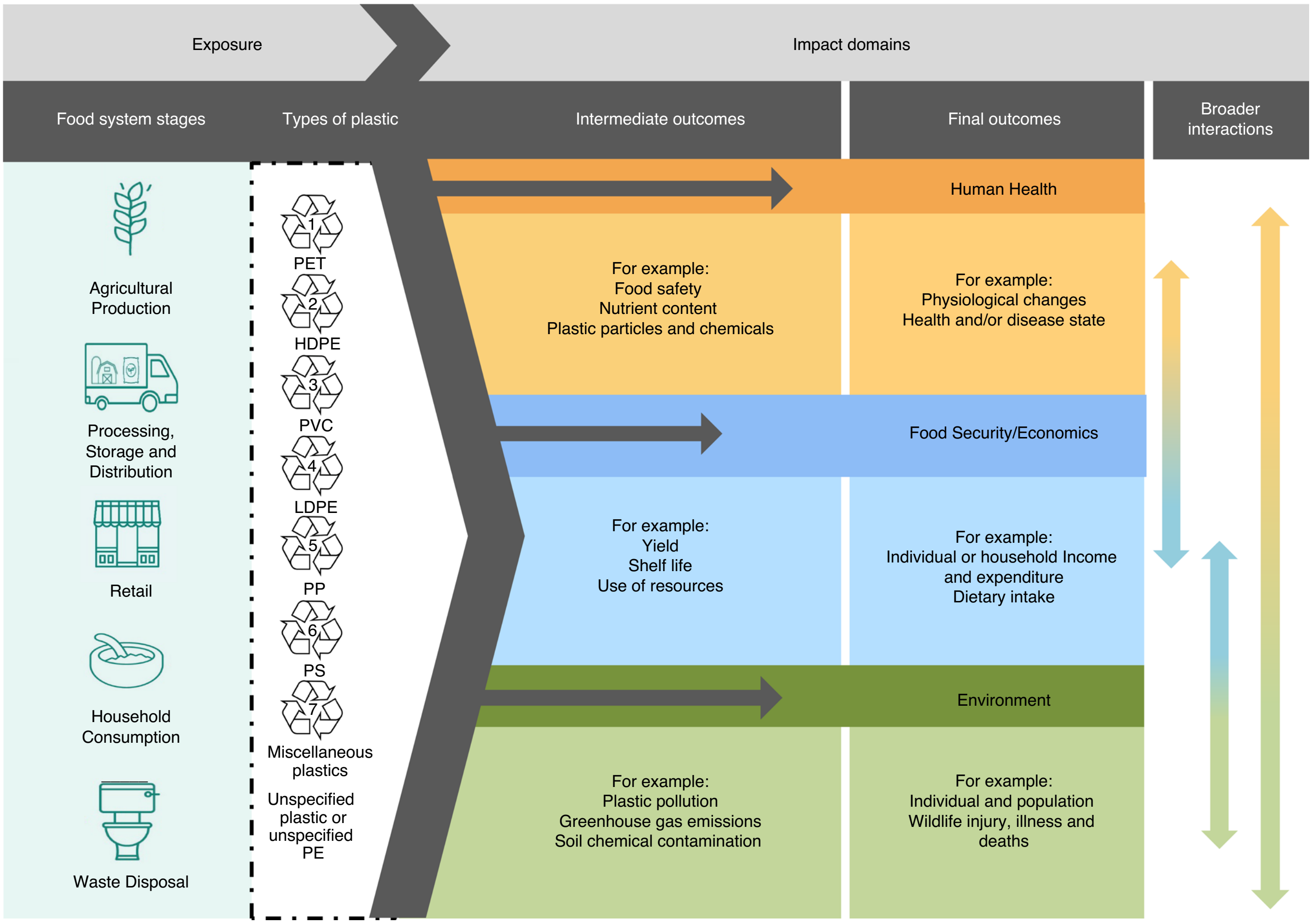

Fig. 1 | The logic model describes potential relationships between food systems' uses of plastics and the intermediate and final outcomes. Non-exhaustive examples of our considered intermediate and final outcomes appear under the impact domains of Human Health, Food Security/Economics and Environment. The food system is adapted from Turner et al.[13] and the Food and Agriculture Organization of the United Nations[14].

Figure 4 and the interactive evidence map show the number of studies by plastic use within each food system subsector and across three impact domains. Plastic mulch, polytunnels and greenhouses predominantly made of unspecified plastic or PE accounted for 89% (n = 1,666 studies) in Agricultural Production, whereas fishing gear, a key input into production activities of the food system, featured least frequently in this subsector (n = 57, 3%). In Processing, Storage and Distribution, plastic packaging primarily made of PE, PP and LDPE was most frequently explored (n = 930, 83.3%). Similarly, in Retail, plastic packaging predominated (n = 313, 90.5%). Grocery bags—a focus of policies around the world—were studied in just 11 of the included publications. Within Household Consumption, pre-packaged food items and domestic products, such as infant feeding bottles and storage containers, featured equally, whereas kitchen surfaces and equipment rarely featured. Refuse sacks and compost containers were the only uses of plastics explored in Waste Disposal.

Over 75% of studies contained at least one outcome that related to individual or Food Security/Economics (n = 2,546), 48% to the Human Health (n = 1,602) and 8% to the Environment (n = 282) outcomes (Fig. 3b), although this category experienced the greatest relative increase in publications between 2000 and 2018 (5,100%). Across all the impact domains, the vast majority of studies presented data that falls under intermediate outcomes, with few demonstrating a full exposure-to-impact pathway, in particular where the Food Security/Economics category was concerned. Within the Human Health category, most studies considered the nutrient content of crops, food or beverages (n = 885, 55.2%), with plastic and chemical contamination of food and estimated human exposure to the same measured in 438 (27.3%) and 134 (8.4%) studies, respectively. We found 47 (2.9%) studies that measured the actual presence of plastic-related chemicals in the human body, using indicators such as urinary concentration of bisphenol A (BPA) and phthalates. Finally, 39 (2.4%) studies investigated final outcomes that related to health conditions, which included diabetes mellitus, autism spectrum disorder, Parkinson's disease and broader measures of disability-adjusted life years.

Range of evidence. *Plastic uses and impacts.* We found a range of exposure–outcome relationships in the literature (Fig. 4 and the interactive evidence map). The most frequent relationships were among perhaps the 'less visible' food system subsectors, such as agricultural plastics used for crop production, and outcomes for on-farm productivity and efficiency, which included yields (n = 1,343), climate control (n = 903), pest and disease control (n = 371) and crop nutrient content (n = 354). In contrast, soil and crop contamination by plastics or related chemicals (n = 45), subsequent human exposure (n = 15) and Environment outcomes were less frequently studied.

In Processing, Storage and Distribution, there was a focus on intermediate Human Health and Food Security/Economics outcomes, which included plastic packaging that affected the nutrient,

Box 1 | Methods summary

Review. Cross-disciplinary scoping review using PRISMA guidelines.

Theoretical framework. Our logic model (Fig. 1) articulates our hypothesized pathways from plastics used in food system subsectors via intermediate outcomes to final impact domains. Our food system concept is adapted from those put forward by the Food and Agriculture Organization of the United Nations[14] and Turner et al.[13].

Exposure. At least one specified plastic type, used within any food system subsectors:

1. Food system subsector exposure:
   - Agricultural Production (which includes the production of animals and plants, fishing activities, farm management)
   - Processing, Storage and Distribution (which include on-farm storage, food processing and onward distribution)
   - Retail (sales and marketing activities, which include restaurants and food outlets)
   - Household Consumption (which includes household food preparation and storage)
   - Waste Disposal (post-consumer food waste processing)
2. Plastic exposure:
   - PET
   - HDPE
   - PVC
   - LDPE
   - PP
   - PS
   - Miscellaneous plastics: PC, PLA, acrylic, fibreglass, nylon or PA and epoxy resins

Outcomes/impact domains.
- Human Health
- Food Security/Economics
- Environment

Databases. English language search from the year 2000 in 9 published databases and 15 grey literature sources.

Key inclusion criteria. Quantifiable evidence from anywhere in the world on the beneficial or harmful effects of plastics explicitly used in food systems, on at least one impact domain.

See Methods and our published protocol for a detailed methodology[15].

bacterial or chemical content of food and drink items ($n=705$), and a range of quality-control and shelf-life related outcomes ($n=574$). Nine studies considered the effect of packaging on final Human Health outcomes, but we found no evidence that linked plastic use at this food system subsector to final Food Security/Economics outcomes, such as changes in income or food security indicators. Over 100 studies in this subsector assessed Environment outcomes, but only three of these quantified the final impacts on individual wildlife and population injury, illness and deaths.

For both the Retail and Household Consumption subsectors, pre-packaged food or drink and domestic items, such as infant feeding bottles, were linked to intermediate outcomes, such as human exposure to plastics and chemicals ($n=97$) and their presence inside the human body ($n=47$), as well as to our final outcomes relating to health or disease state and physiological changes ($n=25$). These items were less commonly linked to Food Security/Economics outcomes ($n=36$ overall) but did feature more frequently at the Environment level, particularly concerning air pollution and greenhouse gas emissions ($n=82$). Although very few studies investigated plastics used in Waste Disposal, at least one explored outcomes under each of the domains.

Specific plastic types and their impacts. Every type of plastic considered in our review has been studied the literature, with an extensive range of outcomes captured (Fig. 5). Some plastic types were more frequently linked to certain outcomes than others: PE and PP were frequently explored in relation to effects on the nutrient or bacterial content of crops and food ($n=445$ and 274, respectively), but only one study considered the effects of PP (commonly used in infant feeding bottles) on the presence of plastics or associated chemicals in the human body. Among the studies that looked at plastics and chemicals in the human body, as well as human health states and/or physiological changes, the most commonly explored types were unspecified plastics, miscellaneous plastics and PET. Despite finding evidence of each major plastic type in our sample, a lack of chemical specification of the plastic exposures was very common.

Nature of the evidence. Food system plastics have been investigated using many study designs, which include experimental, non-experimental and mixed methods (Fig. 6). The majority (85%) of publications employed experimental methods ($n=2,865$ studies), mostly to examine plastics used in Agricultural Production ($n=1,713$). Methods such as observational studies, modelling and life-cycle assessments were used in 591 publications (18%). We found just eight meta-analyses (1.4%), all of which assessed plastic mulching, and three longitudinal cohort studies (<1%). In total, the review captured 14 (<1%) case studies or descriptive cross-sectional studies in which post-mortem or the diagnosis of injury, illness or entanglement were linked to food system plastics.

Discussion

We synthesized research across diverse disciplines to characterize the extent, range and nature of evidence on food system plastics relevant to human health, food security, economic and environmental outcomes. Diverse forms of evidence exist on these interlinkages, but there is a distinct lack of systematic meta-analyses in the literature that could support policy-making and decision-making on plastics in the food system. The vast majority of evidence since 2000 (and 98% of the environmental studies) focuses on MICs and HICs, with little evidence from LICs. Further work is needed to ascertain whether these research trends are consistent with a plastics-oriented environmental Kuznets curve, which indicates a rise and fall in plastic pollution relative to economic development and technological research investment[16].

Despite a rapid increase in planetary health research and ongoing discussion of consumer plastics use (for example, straws and coffee cups, for which we found no specifically targeted studies), only 8% of the included publications captured environmental outcomes. This may be a result of environmental research on plastics using methods that did not fit our inclusion criteria (for example, pollution prevalence studies with no comparator) or that many studies did not disaggregate beyond terms such as 'plastic debris' or 'fishing gear', which presents challenges in ascertaining either the source or the material. Additionally, micro- and nanoplastic particles are often too small to be explicitly linked to a food system use or specific sources. These represent considerable problems for accountability as negative environmental externalities of food system activities and actors become untraceable and ungovernable[17].

Intermediate Food Security/Economics outcomes represented the greatest number of studies in our assessment, which included many studies that measured the effects of plastics on agricultural

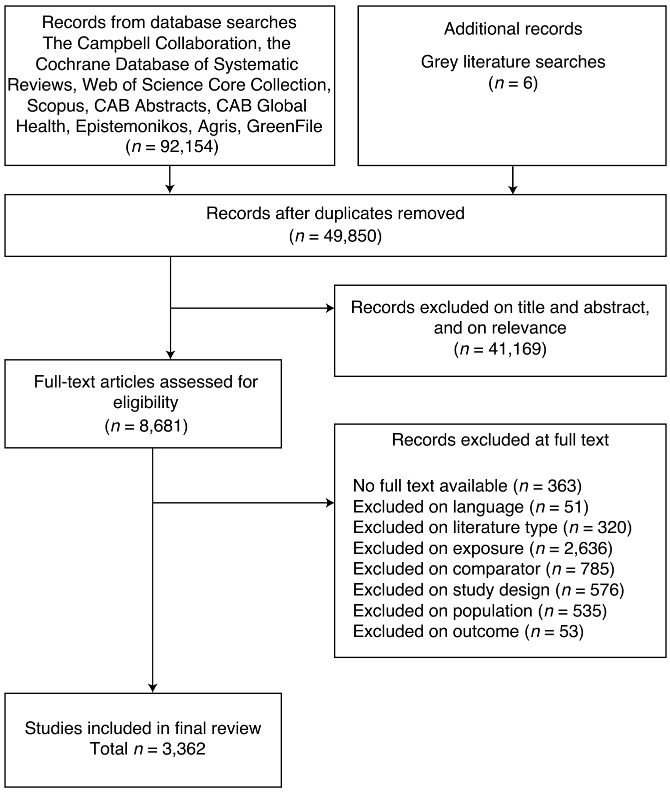

Fig. 2 | Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow chart.

yields and on-farm soil conditions, evidence that may be critical in addressing potential climate-related yield downturns among key staple crops[18,19]. We found evidence to suggest that plastics may provide mitigation and adaptation functions (for example, mulching, tunnels and greenhouses) to improve agricultural productivity and resource efficiency, reduce fertilizer and pesticide use, and mediate CO_2 emissions[20,21]. Nevertheless, we observed an imbalance between research on agricultural productivity versus the quality and safety of crops—these topics require more research or synthesis, particularly in light of debates around possible declines of key food-group nutrients[22]. Few studies investigated the pollution or contamination of crops and soil by agricultural plastics and their associated intentionally and non-intentionally added substances—the one meta-analysis we found for the latter[23] cautioned against short-term gains versus long-term sustainability should environmental measures not be implemented. These asymmetries may echo 'quantity over quality' trends, in which yields, proteins and calories are prioritized over micronutrient-dense crops, production diversity and healthy diets—with consequences for hidden hunger[24].

A large number of studies explored human health, including bacteria control, pathogen barriers and nutrient quality, but few studies presented changes measured or modelled in humans. This gap needs to be filled in all regions—particularly LICs—in which different challenges may drive plastic-use and context-specific trade-offs. Research is needed to model the consequences of removing or substituting plastics in settings that suffer high postharvest losses, persistent foodborne disease and limited infrastructure to support hygienic food environments. Despite these contextual food-safety challenges, we found little research in LICs compared with that in MICs. Similar trends exist among studies that quantify human exposure to food system plastics and associated chemicals, and few explored workplace exposures—33 risk assessments in MIC or HICs and none in LICs. The studies found on plastic packaging, which included the leaching or migration of chemicals and non-intentionally added substances into food or drink, were probably catalysed by research and policy around the effects of plastic-related substances, such as BPA, shown to be dangerous at low doses in young children, with carcinogenic and endocrine disrupting potential in adults[25–27]. Infant feeding bottles that contain BPA are now banned in most industrialized countries, yet in many LICs there remain no such restrictions and little emerging evidence explores the consequences of this policy divergence.

The human health implications of living in the 'Plasticene'[28] appear to be acknowledged at certain supranational levels, as reflected in risk assessments such as the World Health Organization's report on microplastics in drinking water[12] and the European Food Safety Authority's quantification of human exposure to BPA[29]. This review uncovered research that explores exposures to individual uses and groupings of plastics, but we found a lack of interlinking research across food system subsectors, plastic types, uses and outcomes. Thus, we echo wider concerns regarding cumulative exposures to chemicals that emanate from different sectors, which, although different, may have similar effects on the body[30,31]. With moves towards circular economies, in which postconsumer materials are reused or repurposed, potentially toxic substances—known

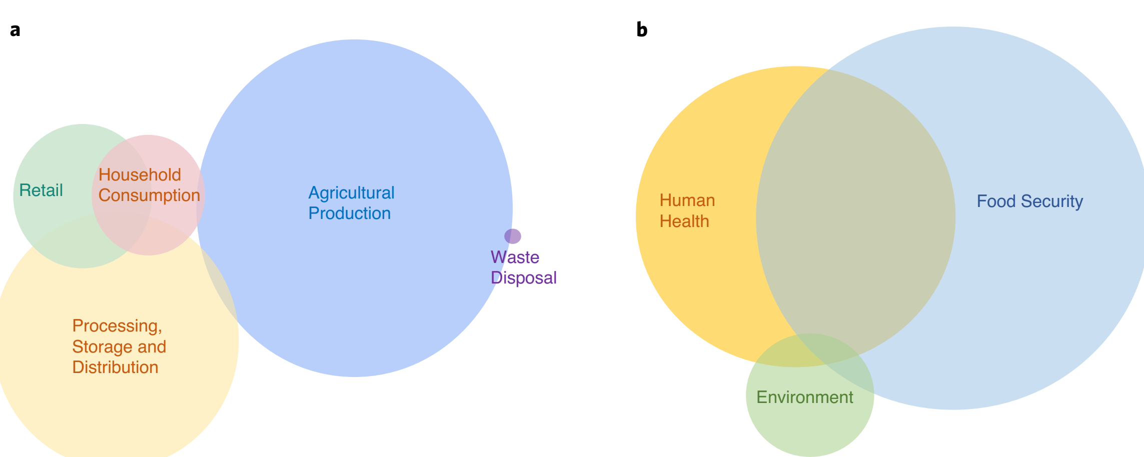

Fig. 3 | Food system subsectors and outcome domains covered in eligible studies for the review. a,**b**, Venn diagrams of the volume of literature found according to food system subsectors (**a**) and by outcome domain (**b**) for all the included studies (*n* = 3,362).

Human Health

	Food/beverage: nutrient content	Food/beverage: bacterial content	Food/beverage: plastic and chemical contamination	Human exposure to plastics and chemicals	Human: internal presence of plastics and chemicals	Human: physiological changes and health
Agricultural Production						
Agricultural input materials	3	0	0	2	0	0
Crop production materials	354	1	18	15	0	6
Farmed animal management materials	8	0	5	1	0	0
Fishing materials	0	0	0	0	0	0
Processing, Storage and Distribution						
Storage and transport materials	56	37	5	10	0	2
Processing site materials	3	10	4	2	0	0
Packaging materials	452	252	165	36	0	9
Retail						
Prepackaged food and bevarage materials	14	21	189	75	6	15
Retail storage and transport materials	0	1	0	4	0	0
Retail and food outlet equipment	0	2	7	0	0	0
Takeaway packaging materials	0	0	5	4	0	0
Shopping materials	0	0	1	2	0	0
Household Consumption						
Domestic kitchen materials	0	3	2	0	3	2
Domestic consumption equipment	2	9	81	24	29	5
Pre-packaged food and beverage materials	2	11	13	33	31	14
Waste Disposal						
Refuse sacks	0	0	0	0	0	1
Food compost containers	0	0	0	0	0	0
All others	0	0	3	0	0	1

Food Security/Economics

	Food system environment	Soil (on-farm): plastic contamination	Resource use (on-farm)	Crop: yield, growth, appearance	Animal: yield, growth, welfare	Pest, weed and disease control	Food/beverage: physical and qualitative attributes	Production economics	Individual/household economics	Individual/household diet quality and intake
Agricultural Production										
Agricultural input materials	9	0	30	13	3	16	2	5	1	0
Crop production materials	903	33	93	1343	0	371	24	142	3	0
Farmed animal management materials	31	0	6	3	73	4	1	5	0	0
Fishing materials	0	0	0	0	12	0	0	1	0	0
Processing, Storage and Distribution										
Storage and transport materials	52	0	1	31	0	65	109	11	1	0
Processing site materials	6	0	2	0	0	1	10	2	0	0
Packaging materials	232	0	2	11	1	34	574	11	0	0
Retail										
Prepackaged food and bevarage materials	9	0	0	1	0	2	15	0	0	0
Retail storage and transport materials	1	0	0	0	0	0	1	0	0	0
Retail and food outlet equipment	0	0	0	0	0	0	2	0	0	0
Takeaway packaging materials	0	0	1	0	0	0	1	0	0	1
Shopping materials	0	0	0	0	0	0	0	0	0	0
Household Consumption										
Domestic kitchen materials	0	0	0	0	0	0	1	0	0	0
Domestic consumption equipment	1	0	1	0	0	2	5	0	0	1
Pre-packaged food and beverage materials	2	1	3	1	1	0	5	2	1	0
Waste Disposal										
Refuse sacks	0	0	0	0	0	0	0	0	0	0
Food compost containers	1	0	1	1	0	0	0	0	0	0
All others	0	0	0	0	0	1	0	0	0	0

Environment

	Soil characteristics	Water characteristics	Air characteristics	Resource use (off-farm)	Ecosystem health	Soil and beaches (off-farm): plastic contamination	Wildlife: plastic ingestion and behaviour change	Wildlife: individual and population injury/deaths
Agricultural Production								
Agricultural input materials	3	3	10	5	4	2	1	3
Crop production materials	15	25	59	21	20	7	2	6
Farmed animal management materials	1	4	3	2	2	0	0	1
Fishing materials	1	12	1	1	0	10	6	28
Processing, Storage and Distribution								
Storage and transport materials	7	13	27	18	15	7	0	1
Processing site materials	1	1	1	1	1	0	0	0
Packaging materials	18	26	82	66	41	12	3	2
Retail								
Prepackaged food and bevarage materials	21	26	77	64	43	9	0	1
Retail storage and transport materials	4	4	8	7	7	1	0	0
Retail and food outlet equipment	0	0	0	0	0	0	0	0
Takeaway packaging materials	2	4	7	6	4	2	0	0
Shopping materials	1	2	8	7	4	1	0	0
Household Consumption								
Domestic kitchen materials	0	0	1	0	0	0	0	0
Domestic consumption equipment	4	5	6	4	4	4	1	2
Pre-packaged food and beverage materials	17	21	61	48	34	12	3	0
Waste Disposal								
Refuse sacks	0	1	2	2	2	1	0	0
Food compost containers	0	0	1	0	1	0	0	0
All others	0	0	0	0	0	0	0	0

No. of studies: Lowest – Highest

Fig. 4 | Plastic use (exposure) and outcome categories under the three impact domains. The heat map cross-references all the included studies ($n=3,362$) to show the number of studies that investigated specific uses of plastic within the food system alongside specific outcome categories under the Human Health, Food Security/Economics and Environment impact domains. Impact domains are split by vertical dashed lines into intermediate (left) and final (right) outcomes.

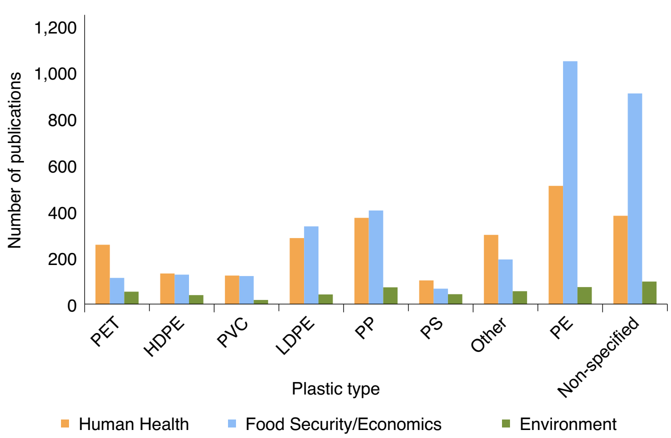

Fig. 5 | Number of publications by plastic type and impact domain.

and unknown—may be inadvertently introduced into foodstuffs. Plastics recycled between food system subsectors (for example, repurposing single-polymer agricultural mulch for food contact materials), may be accompanied by those imported from other economic sectors (for example, repurposing electronic waste for food contact materials). Although this is generally illegal, evidence for these practices exists in several settings and is of particular concern given the divergent sectoral regulatory environments[32,33].

Implications for research and policy. This systematic scoping review includes research across disciplines, and reveals important evidence gaps and highlights datasets that may be suitable for targeted systematic reviews and meta-analyses in different exposure–outcome domains. The interactive map and framework enable broad communities of research, practice and policy to explore existing evidence, and plan work that is collaborative and/or complementary. We hope this will be used to enhance interdisciplinary approaches, inform funding priorities and guide cross-sectoral research agendas to generate the much-needed evidence base for policy decisions across key human health, economic well-being and environmental outcomes.

The four Rs, remove, reduce, reuse and recycle/repurpose, are central among policy responses to the plastic problem and transitions towards circular economies[34]. This review can be used to locate evidence that concerns how, where and with what effects different plastics are used and studied across food systems, and enable further enquiries around substitution or discontinuation. However, our review also suggests that the type of cross-cutting evidence and analysis needed to inform such policies and understand trade-offs across different subsectors and outcomes is either lacking or not yet synthesized adequately. Despite numerous initiatives around food-related plastics[35] (for example, Bangladesh's plastic bag ban or Canada's pledge to remove single-use plastics), we found little analysis of their associated intentional and unintentional beneficial or harmful impacts—particularly around human health and food security.

The COVID-19 pandemic is driving large increases in single-use plastics, particularly in food retail and consumption, as producers

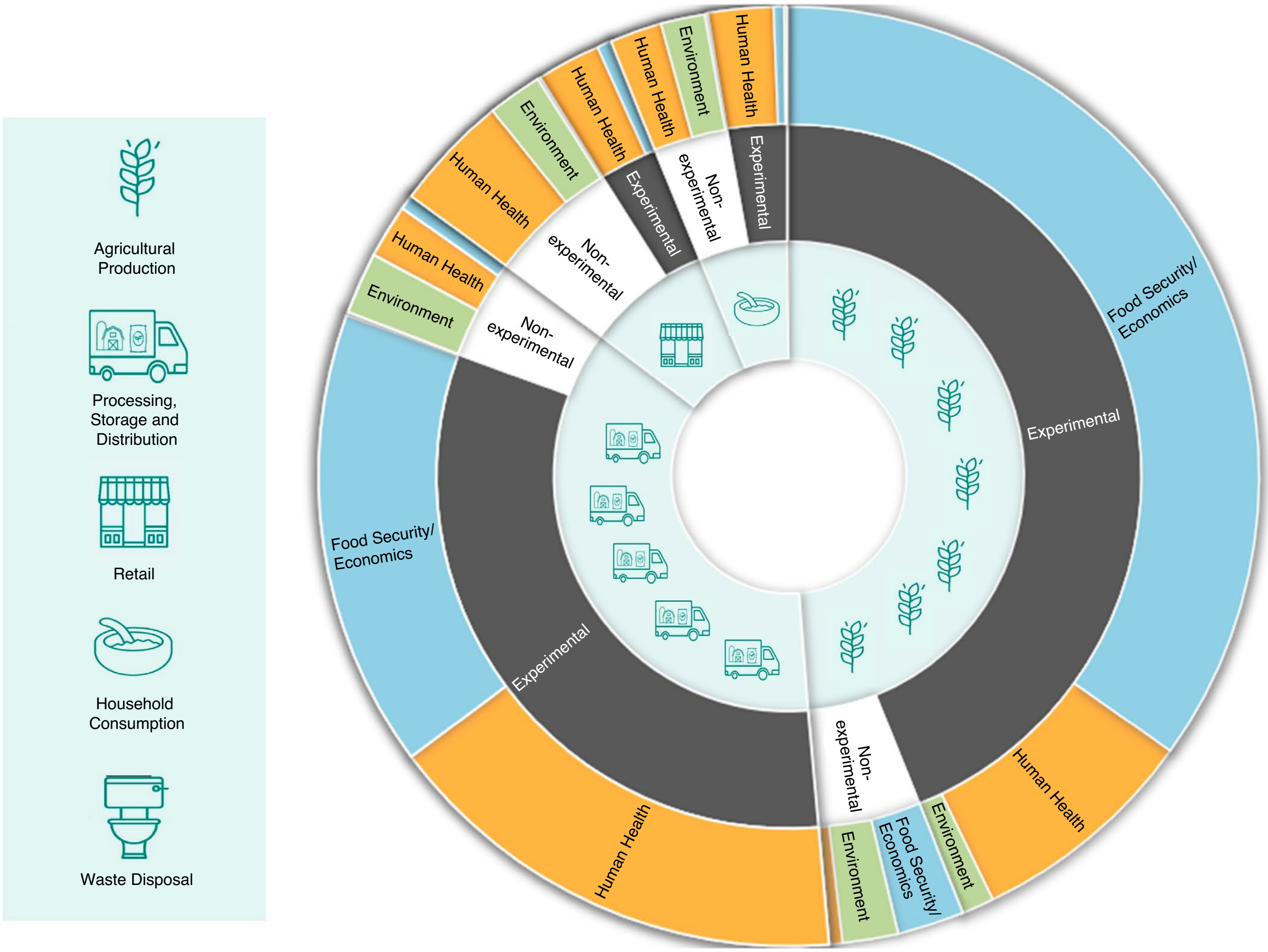

Fig. 6 | Frequency of study designs used to investigate the effects of plastic use in different food system subsectors. Sunburst diagram of all the included studies ($n = 3,362$) showing the frequencies of study designs (experimental versus non-experimental) employed to investigate the effects of plastic used at different levels of the food system and the corresponding frequencies of investigated Human Health, Food Security/Economics or Environment outcomes.

and consumers turn to perceivably more hygienic, disposable options and to online deliveries[36,37]. Recycling activities are reduced as many governments struggle with operations or seek to protect workers from viral transmission[38]. Coupled with the recent oil price decline—and thus the cost of virgin plastics—these developments pose substantial new questions for researchers and policymakers, and also emphasize the bidirectional and interconnecting pathways between food system plastics, human health, food security and the environment. Debates around 'building back better'[39,40] in a post COVID-19 world must take into account how plastics are used across food systems and the range of outcomes they may contribute to—both beneficial and harmful.

Conclusion

This systematic scoping review reveals that plastics are widely used and researched across food systems around the world, with multiple outcomes considered in a rapidly expanding evidence landscape that is both diverse and imbalanced. Exploring these materials through a food system lens and across interdependent sustainability and impact domains illuminates how many trade-offs may exist when transitioning towards circular economies. The extent, range and nature of this evidence highlights a mismatch between the prevailing discourse around consumer-level plastics and research agendas more focused on production, processing and storage. The types of collaborative research needed to account for final outcomes—particularly among human populations – is urgently needed to address food systems' 'plastic problem'.

The findings from this systematic scoping review provide a common roadmap for the formulation of research strategies by diverse stakeholder groups, such as researchers, funders, international agencies and government bodies. It enables disparate research communities to identify gaps and generate the robust cross-disciplinary evidence needed to inform policies to remove, reduce, reuse, recycle or repurpose food system plastics. The interactive evidence gap map is a customizable, shared tool to foster this interdisciplinary collaboration, to augment new research questions, identify mature evidence for systematic reviews and avoid duplication—with implications for sustainable, safe, affordable and nutritious diets (Box 2).

Methods

Scoping reviews are valuable for systematically synthesizing broad-based evidence on topics of intersectoral and interdisciplinary relevance, building bridges and bringing coherence to a diverse evidence base, but they do not assess the direction, quality or bias of evidence[41].

We followed the PRISMA extension for Scoping Reviews guidelines[41] (see Supplementary Methods 1 for a full checklist). We developed a protocol in liaison with technical experts and the Campbell Collaboration[15]. Our logic model (Fig. 1)

Box 2 | Selected recommendations

Extent
Evidence from low-income contexts is severely lacking and therefore urgently needed to ensure that circular economy policies in these settings can account for a range of context-specific beneficial and harmful outcomes for different domains.

Range
Gaps exist in several key areas that could be filled, examples being workplace exposures to food system plastics and the plastic-related chemical contamination of crops or soil.

Although evidence exists on the relationships between some food system plastics and human health (particularly modelled exposures), there is insufficient comparable data to conduct meta-analyses around specific disease states. Where risk assessments exist for chemicals found in plastics known to be used in the food system (for example, BPA or phthalates), traditionally distinct research disciplines could collaborate to 'join the dots' along causal pathways to understand how specific food system plastics may impact humans.

Nature
Plastic types are often not specified in studies, which thus hampers the conduct of meta-analyses. Capturing this information is useful for circular economy actions, substitution endeavours and food system accountability/extended producer responsibility.

Evidence exists for new meta-analyses, particularly where food system plastics may be beneficial for on-farm environments (for example, through limiting resource and fertilizer use). However, understanding the long-term implications of sustaining food security at the expense of incurring on-farm plastic pollution should also be prioritized.

guided the review and describes possible exposure–outcome relationships we expected to find in the literature, and also provides illustrative examples. For the purpose of this study, we use the term 'impact' to cover the effects or outcomes of plastics, for which terminology may differ among disciplines.

The logic model breaks down these impact domains into intermediate and final outcomes. Intermediate outcomes constitute either plausible steps on a pathway to a final outcome, such as contamination of food on the pathway to human health, or a grouping of factors that may precede either irreversible or substantially harmful outcomes within that domain, such as greenhouse gas emissions under Environment.

Eligibility criteria. The primary inclusion criteria for this review was a combined exposure of (1) any food system subsector and (2) any specified type of plastic used within it. Outcomes described in the literature must have fallen within at least one of the specified outcome groupings of human health, the environment or food security/economics, referred to as 'impact domains'. Box 1 outlines the key characteristics of our exposure and outcome eligibility criteria.

Any experimental or non-experimental study design was eligible for inclusion provided the study presented quantitative data in relation to a comparator group. Possible comparator group(s) included a control, exposure to other materials (including other types of plastic), a dose–response relationship (including time exposure) or different environmental conditions or population characteristics that may alter outcomes. Case studies or descriptive cross-sectional studies with a clear cause-of-death diagnosis, injury or entanglement due to plastic, modelling (including risk assessments) and life-cycle assessments were exempt from having a comparator group. We considered any population except for plastic itself. We accepted any geographical location found in studies published from 2000 onwards in the English language. Our date range is due to major evolutions in food systems, plastic use, diets and circular economy legislation, as detailed in our protocol.

Search strategy, data extraction and analysis. We devised the search strategy in consultation with a search specialist, technical experts and librarians at the London School of Hygiene and Tropical Medicine, applying a systematic search of over 200 relevant terms to nine scientific databases (Agris, CAB Abstracts, CAB Global, Campbell Library, Cochrane Database of Systematic Reviews, Epistemonikos, GreenFile, Web of Science and Scopus) as well as 15 grey literature sources between December 2018 and February 2019. A full list of search terms and sources are given in our protocol[15] and in Supplementary Methods 2.

We used EPPI-Reviewer 4 for the reference management, screening, data extraction and analysis. Records were double screened at the title and abstract, with disagreements resolved by a third reviewer, and single screened at the full text stage after training and consistency checks were performed on 10% of the records. The data-extraction form, piloted extensively, included publication date, study location, study design, type of plastic, food system subsector and specific function of the plastic, outcome category and funding source (Supplementary Methods 3). Categories were not mutually exclusive, and a single study could have multiple codes per category. Data extraction was carried out by three researchers with regular training updates and thematic consistency checks on 10% of all the included records. Texts that were not located for a full text screening were coded according to information provided in the abstract so that bias could be highlighted.

We used EPPI-Reviewer 4 and Microsoft Excel for cross-tabulation, frequency distributions and mapping data against our logic model and heat map. This map is also available online as an interactive resource which provides a full list of references for all studies included in this review. We grouped countries according to the World Bank's 2019 assessment of economic incomes for LICs, MICs and HICs[42].

Strengths and limitations. The breadth of this review posed challenges to accommodating diverse research standards and methods from different disciplines. Some studies did not fulfil our inclusion criteria—for example, observational studies of plastics in natural environments often failed to link plastic explicitly to the food system or lacked a suitable comparator. Although many new bio- or plant-based plastics are under development, given their still early development, we utilized the seven major Resin Identification Codes for our selection criteria as they are widely used within the food system. We included non-specified and composite plastics if shown to include a plastic from this list, as well as epoxy resins—a family of plastics commonly used in aluminium food tins; however, some plastics, such as melamine, were not included. Our search was limited to English publications only and, although we demonstrate a wide geographical spread, a broader language inclusion would have yielded additional results.

We utilized distinctions between intermediate and final outcomes as well as where plastic uses occur, which sometimes transcended the food system subsectors. We employed an adapted food system framework, for which we acknowledge many others exist. This approach is subjective and debatable, depending on the particular discipline or point of view of the reader. To address this, we presented data in the interactive map according to our conceptualization and in disaggregated forms so they may be reorganized to suit the requirements of different fields or researchers. Our screening and data extraction strategy sought high levels of accuracy alongside feasibility in managing a large body of research—a much-debated balancing act among systematic review researchers[43]. Although errors may occur, our detailed protocol[15] demonstrates that systematic misclassification of results is unlikely. Finally, our approach does not lend to causal statements between food system plastic exposures and human health, the environment or food security/economics. This is in line with PRISMA scoping review guidelines, which recommend the presentation of current research landscapes to guide future systematic reviews and meta-analyses.

Data availability
The data for this review are available as an open access interactive gap map, accessible online via https://anh-academy.org/foodplastics_EGM.html. The search strategy and coding framework are available as Supplementary Information. Citations of studies eligible in this review are available in alternative formats from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability
The full coding strategy used for data extraction and analysis of studies included in our review is provided in Supplementary Methods 3.

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Author contributions

The project was conceptualized by J.Y., M.D., S. Kalamatianou, and S. Kadiyala. Data were curated by M.D., H.B.R., J.Y. and S.Kadiyala. The formal analysis was by H.B.R., M.D. and J.Y. The investigation was carried out by J.Y., M.D., H.B.R., S. Kadiyala and H.W. The methodology was designed by J.Y., M.D., H.B.R. and S. Kadiyala. H.W. supervised the project. Visualization was by M.D., H.B.R. and J.Y. The original draft was written by J.Y., M.D. and H.B.R., and reviewed and edited by J.Y., M.D., H.B.R., S. Kadiyala and H.W.

Competing interests

The authors declare no competing interests.

Additional information

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