Solid Wastes Provide Breeding Sites, Burrows, and Food for Biological Disease Vectors, and Urban Zoonotic Reservoirs: A Call to Action for Solutions-Based Research

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**Background:** Infectious disease epidemiology and planetary health literature often cite solid waste and plastic pollution as risk factors for vector-borne diseases and urban zoonoses; however, no rigorous reviews of the risks to human health have been published since 1994. This paper aims to identify research gaps and outline potential solutions to interrupt the vicious cycle of solid wastes; disease vectors and reservoirs; infection and disease; and poverty.

**Methods:** We searched peer-reviewed publications from PubMed, Google Scholar, and Stanford Searchworks, and references from relevant articles using the search terms (“disease” OR “epidemiology”) AND (“plastic pollution,” “garbage,” and “trash,” “rubbish,” “refuse,” OR “solid waste”). Abstracts and reports from meetings were included only when they related directly to previously published work. Only articles published in English, Spanish, or Portuguese through 2018 were included, with a focus on post-1994, after the last comprehensive review was published. Cancer, diabetes, and food chain-specific articles were outside the scope and excluded. After completing the literature review, we further limited the literature to “urban zoonotic and biological vector-borne diseases” or to “zoonotic and biological vector-borne diseases of the urban environment.”

**Results:** Urban biological vector-borne diseases, especially *Aedes*-borne diseases, are associated with solid waste accumulation but vector preferences vary over season and region. Urban zoonosis, especially rodent and canine disease reservoirs, are associated with solid waste in urban settings, especially when garbage accumulates over time, creating burrowing sites and food for reservoirs. Although evidence suggests the link between plastic pollution/solid waste and human disease, measurements are not standardized, confounders are not rigorously controlled, and the quality of evidence varies. Here we propose a framework for solutions-based research in three areas: innovation, education, and policy.
Conclusions: Disease epidemics are increasing in scope and scale with urban populations growing, climate change providing newly suitable vector climates, and immunologically naïve populations becoming newly exposed. Sustainable solid waste management is crucial to prevention, specifically in urban environments that favor urban vectors such as Aedes species. We propose that next steps should include more robust epidemiological measurements and propose a framework for solutions-based research.

Keywords: planetary health, infectious disease epidemiology, plastic pollution, vector-borne diseases, urban zoonoses, solid waste

INTRODUCTION

Rationale

The world is in a solid waste and plastic predicament (1–15)—single use-plastic packaging is increasing in an urbanized (11, 16–20) and globalized economy in which production of food happens farther from the consumer and packaging enables consumption far from the source; yet, plastics lack a circular economy (21–23) that would incentivize responsible management (3, 24–28), resulting in large accumulations of solid waste, specifically plastics which do not biodegrade (29).

The most common approach to eliminating accumulated trash in low- and middle-income countries is open burning. For example, in sub-Saharan Africa, more than 75% of waste is openly burned and worldwide an estimated 600 million tons are openly burned annually (30). Open burning of trash is dangerous for human health (6, 31–33) and the planet, as burning releases toxins into the air that pollute the environment and increase greenhouse gases which contribute to climate change (30).

Policies are slowly catching up to reduce single-use plastic supply, but these policies are only one part of a complete solution (34–37) to single-use plastic production, demand, and disposal (29) and these policies often face poor enforcement, especially in LMICs (29).

At the same time, the risk of zoonosis has increased with urbanization (38) and immunologically naïve populations are newly at risk for vector-borne disease transmission due to changing geographies of suitable vector climates (39–41). Vector-borne diseases such as dengue—transmitted by container breeding Aedes spp.—threaten about half a billion people in densely populated areas (42). One very important mosquito vector, Aedes aegypti, which spreads dengue, Zika, chikungunya, and yellow fever, prefers to breed in man-made containers (43, 44), such as recyclable plastic containers, tires, and trash. The 2,050 projections of over 6 billion people living in urban areas (45) suggest an impending increase in the risk of infectious disease transmission.

Objectives

Trash accumulation has been cited as a risk factor for infectious disease (46–50). Recent viewpoints discuss the subject (51–53), but analytical reviews are outdated (54–57). Other reviews exclude key references on trash and disease risk (19, 58–60), while others focus on urbanization or poverty (18, 19, 57). Some reviews take a narrow scope and are pathogen-specific (for example, we identified reviews on trash and dengue virus (61–63), protozoans (64), and leishmania (65)) or vector-specific (arthropods (51)), limited to landfills and incineration (66), microplastic-specific (67), or waste-specific (68). However, the potential risk of direct transmission of infectious diseases by any kind of solid waste depends on a multitude of inter-related factors including, but not limited to, the presence of an infectious agent, its viability in solid waste, and a susceptible host.

We hypothesize that plastic pollution, including unused plastic bottles, containers, and tires, is a major environmental health risk and promotes vector-borne diseases (VBD) such as dengue, chikungunya, Zika, malaria, and other vectors of disease (triatomine, houseflies) and zoonotic reservoirs (rodents and canines).

METHODS

Search Strategy

We conducted a hypothesis-driven review from January to March 2019. Literature was identified by searches of PubMed, Google Scholar, and Stanford Searchworks, and references from relevant articles using the search terms (“disease” OR “epidemiology”) AND (“plastic pollution,” “garbage,” and “trash,” “rubbish,” “refuse,” OR “solid waste”). Abstracts and reports from meetings were included only when they related directly to previously published work. Only articles published in English, Spanish, or Portuguese (translated using https://www.deepl.com/translator) through 2018 were included, with a focus on post-1994 (the publication year of the last rigorous review on the topic). Cancer, diabetes, mechanical vectors, and food chain-specific articles were outside the scope of this review and excluded. The search was not constrained by geography. After completing the literature review, we further limited the literature to only biological vector-borne and zoonotic diseases (see general concepts defined in the Supplementary Material).
SYNTHESIZED FINDINGS: PUBLISHED LITERATURE ON VECTOR-BORNE DISEASES, URBAN ZOONOSIS, AND SOLID WASTE

One hundred and fifty three references were identified in the literature review, 73 of which discussed vector-borne and zoonotic diseases. We discuss vector-borne diseases and urban zoonosis in the context of solid waste and highlight major vectors, reservoirs, and diseases.

We identified 45 references related to vector-borne disease risk and solid waste. We categorized the results according to vector (Aedes species, Phlebotomus spp. (sand flies), triatominae, Anopheles species), pathogen (dengue, chikungunya, and Zika viruses, Leishmania, Trypanosoma cruzi, and Plasmodium) and type of evidence (case study, observational, intervention, policy, or review). We summarize the evidence in Table 1 and details are available in Supplementary Material 1.

We identified 16 references related to urban zoonosis and solid waste. We categorized the results according to vector (rodent and canine), pathogen (Orientia tsutsugamushi, Leptospira, Yersinia pestis, Toxoplasma gondii, and rabies virus) and type of evidence (case study, observational, intervention, policy, or review). We summarize the evidence in Table 2 and details are available in Supplementary Material 2.

Vector-Borne Diseases and Solid Waste

Vector-borne diseases, especially Aedes-borne diseases, are associated with solid waste accumulation in the urban environment, even small cups, and wrappers, but vector preferences vary over season and region. Other vectors are associated with trash as a burrow, source of food, and breeding site.

Aedes Species

Aedes species mosquitoes prefer to breed in man-made plastic containers (43, 44) and transmit dengue (DENV), Zika (ZIKV), and chikungunya (CHIKV) viruses. Aedes albopictus is reported to preferentially breed in solid waste (91), and tires (92), open coconut shells (92, 93) and small plastic containers (92, 93). Aedes aegypti prefers to breed in discarded tires (95, 98) and artificial water containers (95); plastic containers (96), solid waste (96, 98), buckets (97), drums (97), tires (97), pots (97), and garbage dumps (98). Both Aedes albopictus and Aedes aegypti breed in plastic teacups (100, 101), plastic containers (79–82, 102, 103, 128), tires (79, 82, 101), trash (96, 101), bottles (103), and cans (103). However, these associations change seasonally and regionally. During transmission season, Aedes prefers solid waste (96) in Delhi, India. During the rainy season in Brazil, Aedes prefers tires (92), open coconut shells and small plastic containers (92). In India, breeding preference ratio was highest for tires and container breeding during pre-monsoon (79). Human DENV transmission was strongly associated with irregular garbage collection during low transmission periods/interepidemic intervals (44).

At the household-level, the evidence shows an increase of dengue risk with the presence of cans, plastic containers, tires (70), a lack of consistent garbage collection (44, 71, 73, 74, 77), and with garbage accumulation (75).

CHIKV and ZIKV have also been associated with garbage accumulation in ecological models (88, 89). However, ecological models can be subject to biases and residual confounding (76). In a case study, Krystosik, Curtis (129) used spatial video and Google Street View in Cali, Colombia to create sub-neighborhood risk surfaces compared with routinely reported clinical cases of dengue, chikungunya, and Zika. Ministry of Health officials and Community Health Workers perceived proximity to unplanned urbanizations without solid waste management as a risk factor for dengue, chikungunya and Zika hotspots. Lack of sanitation can be systematic, for example, 80–90% of housing on Reunion Island was built by squatters resulting in the absence of adequate drainage systems for sewage and rainwater and the lack of properly organized garbage disposal and providing breeding grounds for vector-borne diseases, especially CHIKV (90).

Conversely, removing trash and stagnant water from around the residence is protective (78, 84–87, 94, 99), especially when the government acts with intention and the community is consistently mobilized (85, 86). However, results depend on the local ecology of vector breeding (83, 87).

Other Vectors

Other vectors use trash as a burrow, source of food, and breeding site. To prevent tick-borne diseases, The US Centers for Disease Control recommends removing old furniture, mattresses, or trash that may give ticks a place to hide (49); however, no other evidence of an association between trash and tick-borne disease was found. Abbasi et al. (111) identified 33 species of arthropods from a Municipal Solid Waste landfill in Urmia, Iran, including medically important species: Periplaneta americana Linnaeus (Blattodea: Blattidae) and Shelfordella lateralis Walker (Blattodea: Ectobiidae). Ahmad et al. (112) report that malaria was associated with low rates of solid waste collection system use. However, this association was based on geospatial analysis that did not control for potential confounders. Others report that Anopheles stephensi also breeds in manufactured containers (130, 131).

Community members in rural India report that visceral leishmaniasis-transmitting sand flies breed in trash (105). In two studies, the risk of visceral leishmaniasis increased in the absence of regular trash collection (104, 106).

In Yucatan Peninsula, Mexico, residents report triatomines, the vectors of Trypanosoma cruzi, burrow in accumulated trash, cardboard, and rocks (110). Strong entomological (109, 110) and clinical (107, 108) evidence supports this local perception. Dumonteil et al. (109) conducted entomological surveillance for one year in 38 randomly selected houses and created crude and adjusted models in which they observed a strong association between the practice of cleaning of trash from the peridomicile and house infestation by non-domiciliated Triatoma dimidiata (109). Fortunately, similar
TABLE 1  | Vector-borne disease evidence.

| Study type | Sample size | Year | Study site | WHO Region | Trash type/risk measured | References |
|------------|-------------|------|------------|------------|--------------------------|------------|
| **Aedes: DENV** | | | | | | |
| **Serosurveys** | | | | | | |
| 106 households (501 residents) | 2000 | El Salvador | Americas | Discarded cans, plastic containers, tire casings | (70) |
| 273 people | 2008 | Texas-Mexico border | Americas | Waste tires and buckets | (43) |
| 600 people | 2004 | Brownsville, Texas, and Matamoros, Tamaulipas, México | Americas | Water-holding containers, garbage collection | (71) |
| **Focus groups** | 59 people | 2003 | San Juan, Puerto Rico | Americas | Insufficient garbage removal | (72) |
| **Surveillance system studies** | | | | | | |
| Case-control study | 34 cases and 34 controls | 2001 | Fortaleza (north-east Brazil) | Americas | No waste collection | (73) |
| Observational study | 219 (139 with and 80 without infection) | 2017 | Machala, Ecuador | Americas | Daily garbage collection | (74) |
| **Surveillance system modeling studies** | | | | | | |
| 4,165 households | 2014 | Thailand | S-E Asia | Outdoor solid waste disposal | (75) |
| 4,248 cases | 2018 | Guayaquil, Ecuador | Americas | Negative association: municipal garbage collection at the census block level | (76) |
| **Population-based case-control study** | 538 clinical cases and 727 controls | 2011 | Campinas, São Paulo, Brazil | Americas | Frequency of garbage collection | (77) |
| **Longitudinal models** | 165 cases; 492 controls | 2018 | Fortaleza, Brazil | Americas | Irregular garbage collection, scrapyards and sites associated with tires | (44) |
| **Case-control study** | 165 cases; 492 controls | 2014 | Guangzhou, China | Western Pacific | Removing trash and stagnant water from around the residence | (78) |
| **Entomological surveys** | | | | | | |
| Larval | 70 clusters; 1,750 houses | 2014 | Thrivananthapuram, Kerala, India | S-E Asia | Tires and containers | (79) |
| Larval | 789 breeding habitats | 2008–2009 | Malaysia | Western Pacific | Plastic containers as breeding habitats | (80) |
| | 205 households | September 2017 | Five streets in urban Chidambaram, Cuddalore district, Tamil Nadu state, India | S-E Asia | Discarded plastic containers | (81) |
| Larval | 347 DF/DHF cases in 120 study sites | July 2002–August 2003 | Kandy District, Sri Lanka | S-E Asia | Tires, discarded plastic | (82) |
| **Intervention studies** | | | | | | |
| Modeled a hypothetical sanitation program | 1999 | Montrose urbanization in Caroni County and Port Currama in the St. Andrews/St. David district, Trinidad | Americas | No effect: tires and small miscellaneous discarded trash | (83) |
| Waste disposal act | 1988–1993 | Taiwan | Western Pacific | Discarded containers | (84) |
| Household level waste management intervention for vector control and community mobilization | 200 houses | 2012 | Gampaha district of Sri Lanka | S-E Asia | Waste management at household level, the promotion of composting biodegradable household waste, raising awareness on the importance of solid waste management in dengue control and improving garbage collection bowls, tins, bottles | (85) |
### TABLE 1 | Continued

| Study type                                              | Sample size | Year | Study site                                      | WHO Region (59) | Trash type/risk measured                                                                 | References |
|---------------------------------------------------------|-------------|------|------------------------------------------------|-----------------|------------------------------------------------------------------------------------------|------------|
| Community-centered dengue-ecosystem management           |             | 2012 | Yogyakarta city, Indonesia                      | S-E Asia        | Solid waste management and recycling                                                      | (66)       |
|                                                         |             | 2006 and 2011 | India, Sri Lanka, Indonesia, Myanmar, Philippines, Thailand | S-E Asia/Western Pacific | Solid waste management, composting and recycling schemes small discarded containers         | (67)       |
| **Aedes: ZIKV/CHIKV**                                   |             |      |                                                |                 |                                                                                           |            |
| Surveillance system modeling studies                     |             | 2014–2016 | Brazil                                        | Americas        | Man-made larval habitats and environmental management—water supply/storage and solid waste management as measured by the Garbage accumulation index (number of houses with accumulated and uncollected garbage) | (68)       |
|                                                         |             | 2018 | Brazil                                        | Americas        | Reported garbage destination, type of sanitary installation                               | (69)       |
| **Aedes: CHIKV**                                        |             |      |                                                |                 |                                                                                           |            |
| Policy brief                                            |             | June 2012 | Reunion Island                                | Africa          | Garbage disposal                                                                         | (90)       |
| **Aedes albopictus**                                    |             |      |                                                |                 |                                                                                           |            |
| **Intervention studies**                                |             |      |                                                |                 |                                                                                           |            |
| Larval                                                  | 3720 premises and 820 local inhabitants | 2010 | Sant Cugat, Spain                             | Europe          | Premises with solid waste                                                                  | (91)       |
| Immatures                                               | four city areas | 2007 | Fortaleza, Ceará, Brazil                      | Americas        | Tires, opened coconuts and small plastic containers                                       | (92)       |
| Larvae                                                  | 100 homes   | 2006–2009 | Calicut, Kerala, India                       | S-E Asia        | Coconut shells and plastic waste                                                          | (93)       |
| **Aedes aegypti**                                       |             |      |                                                |                 |                                                                                           |            |
| **Intervention studies**                                |             |      |                                                |                 |                                                                                           |            |
| Larval                                                  | 750 containers; 1,873 larvae | May–June to September-October 2014 | Dire Dawa, East Ethiopia                     | Africa          | Discarded tires and artificial water containers in houses and peridomestic areas           | (95)       |
| Immature                                               | 18 localities | June 2013 to May 2014 | Delhi, India                                  | S-E Asia        | Solid waste and plastic containers                                                         | (96)       |
| Temporal dynamics and spatial patterns                  | 20 sentinel houses in each of 4 study sites | June 2014 to May 2016 | rural and urban sites in western and coastal Kenya | Africa          | Buckets, drums, tires, and pots                                                           | (97)       |
| **Aedes spp.**                                          |             |      |                                                |                 |                                                                                           |            |
| **Intervention studies**                                |             |      |                                                |                 |                                                                                           |            |
| Larval                                                  | 17,815 fixed sites | 2016 | Tartagal, Salta Province, Argentina           | Americas        | Municipal garbage dump, tire repair shops, and small garbage accumulation sites           | (98)       |
| **Aedes albopictus**                                    |             |      |                                                |                 |                                                                                           |            |
| **Intervention studies**                                |             |      |                                                |                 |                                                                                           |            |
| Larval                                                  | 175 discardable plastic teacups | 2003 | Coastal district, Ernakulam, in Kerala State, India | S-E Asia        | Plastic teacups discarded at tea carts                                                     | (100)      |

(Continued)
### TABLE 1 | Continued

| Study type | Sample size | Year       | Study site                          | WHO Region (69) | Trash type/risk measured                                                                 | References |
|------------|-------------|------------|-------------------------------------|-----------------|------------------------------------------------------------------------------------------|------------|
| Immatures  |             | 2012       | Delhi and Haryana, India            | S-E Asia        | Discarded trash, tires and plastic cups at roadside near tea stalls                       | (101)      |
| Larval     | 26 types of wastes | 2015       | Kolkata, India                      | S-E Asia        | Household wastes: earthen, porcelain, plastic, and coconut shells                        | (102)      |
| Larval     | 262 containers | 2009       | University of Malaya, Kuala Lumpur  | Western Pacific | Plastic containers, bottles, and cans                                                   | (103)      |
| Sandflies: leishmaniasis | Two large outbreaks of at least 1,000 newly reported cases | 2005       | Teresina, Brazil                    | Americas        | Regular trash collection                                                                 | (104)      |
| KAP        | 3,968 heads of households | 2006       | Bihar state, India                  | S-E Asia        | Garbage collection                                                                       | (105)      |
| Retrospective study | Five time periods; 3,252 cases | 1990–2014 | Rio Grande do Norte, Brazil         | Americas        | Lack of garbage collection                                                               | (106)      |
| Triatomine: trypanosoma cruzi | 26 rural communities; 905 households, 2,156 humans, and 333 dogs | January 2005–December 2008 | Parroquia San Miguel, Municipio Urbaneita, Estado Lara, Venezuela | Americas        | Household disarray (measured as old and/or damaged artifacts accumulated, materials from construction, inadequate cleaning and free rubbish in the home) | (107)      |
| Entomological surveys: mixed modeling approach | 15 municipalities; 96 villages; 576 dwellings | 2017       | Sucre State, Venezuela              | Americas        | Accumulated garbage as measured by method of garbage disposal                           | (108)      |
| KAP        | Three villages; 570, 702, and 416 houses | 2014       | Yucatan Peninsula, Mexico           | Americas        | Cleaning of trash from the peridomicile                                                  | (109)      |
| Entomological surveys: mixed modeling approach | 1,913 arthropod samples | 2019       | Urmia, Iran                         | Eastern Mediterranean | Municipal solid waste landfill | (111)      |
| Anopheles spp.: Malaria | Geospatial analysis | 450 water samples | Rawalpindi, Pakistan                | Eastern Mediterranean | Low rates of solid waste collection system use | (112)      |

KAP, Knowledge, attitude, and practice. One study found no effect (103) and one other found a negative association (93).

### Urban Zoonosis Associated With Solid Waste

Urban zoonoses, specifically those transmitted by rodent and canine reservoirs, are associated with solid waste, especially when garbage accumulates over time creating burrowing sites and food for reservoirs.

In a review of neglected tropical diseases and their impact on global health and development (50), Hotez states of zoonoses: “Of relevance to the NTDs, the poorest favelas do not benefit from regular garbage collection or sewage treatment, thereby creating excellent niches for rats and stray dogs.” Rodents and canines directly transmit disease of importance to urban zoonosis (123, 125, 132). Solid waste accumulation is an important factor for urban rodent and canine feeding and sheltering strategies. To Aedes interventions, environmental cleanup is associated with decreased risk of triatomine infestation (110). Clinical evidence also supports these findings. Trypanosoma cruzi infection seroprevalence in Venezuela was associated with the increase of accumulated garbage (108) and household disarray (measured as old and/or damaged artifacts accumulated, materials from construction, inadequate cleaning and free rubbish in the home) (107). Bonfante-Cabarcas et al. (107) speculate that accumulated garbage favors breeding of T. cruzi reservoirs (rats, mice, and opossum) and provides long-term refuge with immediate food sources for insects to reproduce and colonize the house for a long time, increasing the probability of intra-domiciliary vector transmission of T. cruzi.
### TABLE 2 | Urban zoonosis evidence.

| Study type                | Sample size                          | Year                  | Study site                                      | WHO Region (69) | Trash type/risk measured                                                                 | References |
|---------------------------|--------------------------------------|-----------------------|------------------------------------------------|----------------|------------------------------------------------------------------------------------------|------------|
| Observational studies     |                                      |                       |                                                |                |                                                                                          |            |
| Surveillance              |                                      | 1984–2011             | Marseille, France                               | Europe         | Garbage collection strikes in which garbage is left on the street                        | (113)      |
|                           |                                      | 3,171 slum residents  | April 2003 and May 2004                         | Americas       | Residence ~20 meters from accumulated refuse                                             | (114)      |
|                           |                                      |                       | Slum in Salvador, Brazil                        | Americas       | Public garbage collection service                                                        | (115)      |
| Outbreak                  |                                      | 1996                  | Western Region of Rio de Janeiro               | Americas       | Lower access to solid waste collection ~% households served by municipal solid waste collection (accumulation of organic wastes, promoting the proliferation of rodents) | (116)      |
|                           |                                      | 87 leptospirosis cases| 1996                                      | Americas       | Waste accumulation                                                                      | (117)      |
| Cross-sectional KAP       | 257 residents                        | May and June 2007     | Urban slum community in Salvador, Brazil       | Americas       | Improving trash collection                                                              | (118)      |
| Outbreak & hospital-based surveillance | 89 confirmed cases, 22 households with index cases and 52 control households located in the same slum communities | 2001 | Slum communities in Salvador, Brazil          | Americas       | Trash collections                                                                       | (48)       |
| Population based case-control study | 66 lab-confirmed cases and 125 age and sex-matched healthy neighborhood controls | October 2000 and March 2001 | Salvador, Brazil                               | Americas       | no association: Peri-domiciliary trash accumulation (Visual inspection of accumulated trash & continuous presence of household trash within five meters of a residence—proximity to accumulated trash) and municipal waste collection | (119)      |
| Rodent: scrub typhus (Orientia tsutsugamushi) | Observational | 2,002 adults | Vientiane City, Laos | S-E Asia | Poor sanitary conditions (presence of rubbish, animal excrement, etc.) | (120)      |
| Rodent: bubonic plague    |                                      |                       |                                                |                | Informal solid waste storage sites, solid waste management                              | (121)      |
| Observational: case study | 1900                                 | Central Sydney, Australia | Australia | Western Pacific | Debris found around the household areas: buckets, pails, jars, barrels, and old tires | (122)      |
| Observational: outbreak study | 1995–1998                           | Mahajanga, Madagascar | Africa | Debris found around the household areas: buckets, pails, jars, barrels, and old tires | (123)      |
| Water studies             | 22 water samples                     | Southern Chile        | Americas | Informal solid waste storage sites, solid waste management                              | (124)      |
| Water studies             |                                      | Peruvian Amazon region of Iquitos | Americas | Clearing away garbage in urban areas                                                    | (125)      |
| Observational             | 888 patients reported clinically     | 1975                  | Salvador                                       | Americas       | Sewage, rats, water, dogs, mud and garbage,                                              | (126)      |
|                           | 236 households                       |                       | Southern Chile                                  | Americas       | Open containers and debris presence of dogs and rodents                                  | (123)      |
| Canine: toxoplasmosis     |                                      |                       |                                                |                | Yard cleaning frequency, and having a dirty yard                                        | (127)      |
| Observation: serosurvey of humans and dogs | 564 households, which included 597 owners and 729 dogs | Urban areas of a major cities, Londrina, southern Brazil | Americas | Yard cleaning frequency, and having a dirty yard                                        | (126)      |
| Canine: rabies            |                                      | 2005–2016             | Lebanon                                        | Eastern Mediterranean | Local garbage crisis: standing accumulated waste                                 | (127)      |

One study found no association (119).
(126) and can be used as a proxy in the absence of reliable data on rodent distribution in the city (117, 126). Presence of rubbish increased risk of scrub typhus (120); Toxoplasma infection in owners and their domiciled dogs was associated with dirty yards (126); and the bubonic plague has historically been associated with solid waste (121, 122).

For example, Kassir et al. (127) conducted an observational study to investigate the risk of rabies and the neighboring Syrian war and the local garbage crisis, finding both were concomitant with a notable increase in the number of dog bites and thus possible rabies exposure. The evidence lies in a time-series of data from the Lebanese Ministry of Public Health (LMOPH) Epidemiological Surveillance Unit public database from 2005 to 2016. A sharp increase in reported animal bites was reported post-2013 (1,004 ± 272 vs. 355 ± 145 bites per year). The authors explain:

“The accumulation of wastes in dumpsites led to the declaration of a severe problem in July 2015, and these open garbage dump sites have been previously shown to contribute to the rise in the number of stray dogs which amplifies the number of possible vectors. Garbage dumps are breeding areas of stray dogs, and if they are no longer around, dogs will migrate to other places. This is reflected by the peak in the stray to domestic dog ratio in October 2015, after heaps of garbage had been covering the Lebanese streets for several months. October, in fact, witnesses the beginning of the rain season in Lebanon, and the rainfall in the presence of open garbage dumps leads to the formation of leachate, a polluting by-product of organic matter. This poses both social and environmental problems such as nuisance, diseases and the spread of stray dogs and other harmful animals. This rise in stray dogs increases the possibility both of new vectors as well as new bites. It is noteworthy that this predominance of stray dog bites was only observed in October 2015, while it was not present in either 2013 or 2014. This further strengthens the correlation between the garbage crisis, a special circumstance of October 2015, and the increase in stray dog bites” (127).

Leptospirosis is associated with dogs (123, 125), accumulated refuse (114), garbage (113, 123) and open containers and debris in the peri-domestic area (123, 125). For example, leptospirosis emergence in Marseille, France is linked to garbage collection strikes that contribute to the expansion of the rat population (113). Among slum residents from Salvador, Brazil, residence <20 m from accumulated refuse was associated with increased odds of previous Leptospira infection (114). Residents of another urban slum in Salvador identified improving trash collection as necessary to control leptospirosis in their community and reported current payment for private trash collection service to avoid trash accumulation in their community or a willingness to pay for this service. Residents reported removing trash on a daily basis but identified that trash cans are >50 m from their homes (118). Leptospira interrogans and L. icterohaemorrhagiae are pathogens of severe diseases that may cluster in urban areas where trash accumulates (123) but are also found in rural households in peri-domestic open containers (debris found around the household areas including buckets, pails, jars, barrels, and old tires) (123). Evidence shows leptospirosis infection clusters at the household level (48). During a leptospirosis outbreak in Western Rio de Janeiro, Brazil, cases were associated with lower access to solid waste collection, measured as a percentage of households served by municipal solid waste collection (116), and waste accumulation was used as an indicator of probable rat presence (117).

Conversely, in Federal District Brazil, leptospirosis infection was negatively associated with population access to public services: sewage network, treated water network, and public garbage collection services (115); and in Salvador, Brazil, there was no association between leptospirosis infection and peri-domiciliary trash accumulation (119).

Framework for Solutions-Based Research
Here we propose a framework for solutions-based research in three areas: innovation, education, and policy.

Lessons Learned From Previously Proposed Frameworks
Efforts to promote circular economies in plastics are gaining international attention (29, 133, 134). The United Nations Environment Programme published 'Single-Use Plastics: A Roadmap for Sustainability, 2018' (29). However, it noted policies and regulations have recently been established and lack monitoring and accountability and suffer from poor implementation. Hawken discusses the short and long term costs and benefits to multiple solutions to Reverse Global Warming (133). However, the solutions require significant investment from business and government to change without a focus on upstream education and innovation. Precious Plastics (134) focuses on the community engagement aspects of reusing plastics but fails to integrate with upstream policy. Examples of successful recycling exist in the metals industry (135–137)—aluminum (135, 136), and steel (137) are recycled and traded as commodities globally.

Perhaps the most common framework is “re-use, reduce, and recycle.” Reusing and recycling receive ample attention given the technology involved, yet trends in the recycling industry are changing: China is no longer accepting foreign trash for recycling (138). Reusing is also challenging as few types of plastics are highly coveted and reusable. The poorer quality plastics are simply trash—unable to be reused or recycled. Therefore, while reusing/recycling/introducing plastic alternatives all have their place, reducing the consumption and sale of single-use plastics is key. Therefore, we are adapting the previously touted framework, emphasizing reduction, and encouraging a circular economy for re-use and recycle.

Building on previous frameworks (29, 133–137), we propose a framework (Figure 1) to reduce vector-borne disease risk and urban zoonoses from exposure to solid waste. Given the importance of intervening at the interface of solid-waste and disease-vectors-and-reservoirs, the framework creates a knowledge-to-action plan using policy and innovative plastic alternatives to decrease the upstream plastic supply, education and art to decrease the downstream global demand for plastic, and innovation to generate profitable uses for currently produced and consumed single-use plastics. The desired result is an action plan to create a circular economy of trash and reduce...
the supply and demand of single-use plastics and to cultivate empowered, educated, and healthy communities that resist trash accumulation to improve health via reduced vector-borne diseases and improved air quality. The expected impact relates to the critical need to understand how the complex system that generates and discards so much trash might be tweaked, so that less trash is produced or trash is put back into either the economic or ecological cycle. As current options are insufficient, we propose solution-oriented research to either better adapt these options or to create whole new options for plastics disposal, recycling, and reuse and discover possibilities for a future without disposable plastics through policy, education, and innovation. The evidence is summarized in Figure 1 and details are available in Supplementary Material 3.

Upstream Innovation Research
Profitable upstream innovation research can decrease supply and improve the processing of solid wastes in an increasingly urbanized and market-based world. Immediate barriers are cost and scalability.

In his 2017 best-seller, Drawdown (133), Hawken discusses the possibility of converting up to 90% of current fossil-fuel based plastic production to bio-based production. However, he warns that the solution must include proper separation and processing to fulfill the goal of sustainable material. Innovation in this field is currently working to drop the price below that of current fossil-fuel-based production. According to a special report commission by the European Polysaccharide Network of Excellence and European Bioplastics, 90% of current plastics could be derived from plants (139). Zhang et al. (140) analyze sustainable materials, defined as a class of materials that are derived from renewable feedstocks and exhibit closed-loop life cycles including aliphatic polyesters and polycarbonates. They also discuss recent advancements that lower the technological barriers for developing more sustainable replacements for petroleum-based plastics including biopolymers (141–143) and agro polymers (144–146).

Two aspects of sustainable materials to consider are biodegradation (147–149) and bioremediation (150–155). Narancic and O’Connor (150–152, 156). We found bioremediation—whereby animals and bacteria can break down plastics into biodegradable products—to be particularly interesting. Narancic and O’Connor (156) review the advances and possibilities in the biotransformation and biodegradation of oil-based plastics, including bio-based and biodegradable polymers, end-of-life management of biodegradables, and a circular economy to reduce plastic waste pollution. New fungi species are biodegrading polyester polyurethane: Pestalotiopsis species (150) and Aspergillus tubingensis (151). Ideonella sakaiensis bacteria break PET (Polyethylene terephthalate) into
terephthalic acid and ethylene glycol in 2 weeks (152). Mealworm larvae can digest Styrofoam in <24 h with no cost to survival over 1 month, converting 47.7% of the ingested Styrofoam into CO$_2$ and biodegradable residue (153, 154). Wax moth *Galleria mellonella* caterpillars can biodegrade polyethylene bags (155). These methods are especially attractive as they require no behavior change and are sustainable and, in some cases, beneficial to the species performing the biodegradation. Yet, these pilot studies need to be studied at scale and adapted to local context to understand feasibility.

Repurposing trash for profit seems like a viable market-based solution (134, 157–161) but does carry some risk of exposure to contamination (162–164) for entrepreneurs and end-users depending on the type of materials and the processes used and this risk should be taken into consideration early in the process. One popular use case is waste-to-energy analyzes waste-to-energy strategies and concludes that for a net implementation cost of $36 billion, a net operational savings of $19.82 billion and 1.1 gigatons of CO$_2$ reduction could be gained. For example, Sweden currently converts 50% of household wastes to energy (161). Yet, Haken warns that this is only a transitional strategy, citing emissions of heavy metals and toxic compounds, even in state-of-the-art facilities. Several reviews discuss waste-to-energy regarding technological options and challenges (165–169), integrated solid waste management in developing countries (170, 171), and the environmental impact (172, 173).

These innovations must come equipped with a knowledge-to-action plan and pilots of these small-scale or theoretical solutions and engagement of external stakeholders such as existing companies, policymakers, and community groups.

**Upstream Policy**

Policymakers are uniquely positioned to make political and normative changes relatively quickly but struggle with enforcement, sustainability subject to elected officials, and community buy-in.

Policymakers are uniquely positioned to prevent and solve public health crises, in collaboration with public health officials and communities (84, 174–176). For example, Chen et al. (84) reported that discarded containers account for 25.4% of *Aedes* vector breeding sites in endemic regions of Taiwan pre-intervention. In 1988, the Waste Disposal Act was amended to make manufacturers, importers, and distributors responsible for the proper recovery, treatment, and recycling of packaging and containers which become an environmental menace. Non-compliance resulted in business suspension. A waste recycling system was established, and a breeding site reduction campaign was promoted for waste management. The authors reported a 98% decrease in dengue incidence reported to the Department of Health from 1988 to 1993. Several countries in Africa continue to implement bans to curb single-use plastic bags which clog drains, sewage systems, or hold rainwater, create breeding grounds for vectors (34).

Experts call for more policy solutions (177–179) and there is evidence that policy agendas can be influenced by popular norms (34, 180). Others argue that informal associations such as waste-picker cooperatives (35, 36, 181, 182) should be strengthened to improve solid waste systems. However, enforcement of such policies may be difficult, especially for nations with challenging processes or non-existent systems (37), and others call for a more community-based approach to increase participation in sustainable waste management (183–185). Businesses that use disposable packaging can also be engaged through social pressure and responsibility to adopt sustainable corporate practices (186, 187) and recoup disposable packaging for recycling.

**Downstream Education to Decrease Demand**

Community-based education and communication have the potential to change norms and create sustainable change but require greater initial investments to tailor and iterate community-based approaches.

Eagle et al. (188) argue that social marketing principles (183, 189, 190) paired with education (75, 85–87, 182, 183, 189–191) and policy (section upstream policy) can intervene to change behavior to positively impact plastic pollution using a transdisciplinary approach to identify barriers to and enablers of sustained behavior change.

Creating awareness about the crisis and health and environmental risks surrounding plastic pollution will not immediately decrease supply, but information may increase social pressure and responsibility to adopt sustainable practices at household (75, 85, 183, 192), community (75, 86, 87, 99, 183, 191, 193–196), and corporate levels (186, 187) that may decrease demand in the future (see details in Supplementary Material 3). For example, Sommerfeld et al. (87) summarize a 5-year research and capacity-building initiative conducted in South Asia and South-East Asia. The initiative developed community-based interventions aimed at reducing dengue vector breeding and viral transmission. Where small discarded containers presented the main problem, groups experimented with solid waste management, composting and recycling schemes. Many intervention tools were locally produced, and all tools were implemented through community partnership strategies. All sites developed socially- and culturally-appropriate health education materials. The study also mobilized and empowered women, students, and community groups and at several sites organized new volunteer groups for environmental health.

Tana et al. (86) built an innovative community-centered dengue-ecosystem management intervention in Yogyakarta city, Indonesia and assessed the process and results. The intervention results included: better community knowledge, attitude, and practices in dengue prevention; increased household and community participation; improved partnership including a variety of stakeholders with prospects for sustainability; vector control efforts refocused on environmental and health issues; increased community ownership of dengue vector management including broader community development activities such as solid waste management and recycling. Tana et al. (86) note, the community-centered approach needs a lot of effort at the beginning but has better prospects for sustainability than the vertical "top-down" approach.
DISCUSSION

Summary of Main Findings

Although evidence suggests the link between plastic pollution/solid waste and human disease, measurements are not standardized, confounders are not rigorously controlled, and the quality of evidence varies.

Here we have reviewed the available evidence for solid waste accumulation impact on biological vector-borne diseases. We hypothesized that plastic pollution, including unused plastic bottles, containers, plastic bags, and tires, is a major environmental health risk and promotes vector-borne diseases (VBD) such as dengue, chikungunya, Zika, malaria, and other VBD transmission. We conclude that solid waste accumulation is a risk factor for zoonotic and vector-borne disease transmission. However, measurements are not standardized, (107, 123, 197) and confounders are not rigorously controlled (106, 112, 123, 197, 198).

In the context of vicious cycles of solid waste accumulation, poor health, and poverty, policymakers use estimates of disease transmission, burden, and risk to inform the allocation of limited public health resources; thus, it is imperative epidemiological estimates control for known confounders and employ standardized measurement constructs (Table 3). Additionally, if surveillance data are used, hybrid surveillance (199, 200) should be employed to correct for known surveillance biases. A framework for solutions-based research is also critical to guide research priorities.

Of note, the landscape of single-use plastics innovations and policy is developing rapidly. For example, Christensen et al. described in April 2019 a next-generation plastic to incentivize recycling in closed-loop life cycles (201, 202). This new plastic can be disassembled and reassembled without loss of performance or quality, even in mixed waste streams (201). And the political trend is gaining momentum—in May 2019, 187 countries agreed to add plastics to the Basel Convention, a treaty that regulates the movement of hazardous materials from one country to another (202).

Limitations

We only included published literature and abstracts in English, Spanish, and Portuguese. We did not have access to primary data and relied on the interpretation of the publishing authors.

| Construct | Measurement | Unit | Covariates | Data source | References |
|-----------|-------------|------|------------|-------------|------------|
| Exposure  | Distance to accumulated trash | Meters | Frequency of trash collection, size, and type of dump | Local mapping | (98, 114, 117, 119, 129, 182) |
| Persistence of accumulated trash | Meters | Frequency of trash collection, size, and type of dump | MOH/Local mapping | (117, 129, 182) |
| Vector breeding in trash | Days | Types of trash | Local mapping | (119) |
| Disease Reservoir associated with trash | Vector counts | Species, seasonality, infection rates, rainfall, temperature, trash type, trash persistence | Entomological surveys | (79–82, 91–93, 95–98, 100–103, 109, 111) |
| Pathogen in trash | Reservoir counts | Species, seasonality, infection rates, flooding, food sources, trash type, trash persistence | Animal Surveys | (113, 114, 123, 126, 127) |
| Access to municipal trash collection | Method of trash disposal | Categorical | Frequency of trash collection, size and type of dump | MOH/Local mapping | (108) |
| Population coverage | Percent by region | Distance to trash collection point, cost of service, types of trash accepted | MOH/Local mapping | (116, 117, 119) |
| Frequency of collection | Days | Distance to trash collection point, cost of service, types of trash accepted | MOH/Local mapping | (77) |
| Distance to trash collection point | Meters | Security of accessing trash collection point | MOH/Local mapping | (129) |
| Cost of service | Local monetary unit | Frequency of collection | MOH/Local mapping | (118) |
| Access to municipal sewage system | Population coverage | Percent by region | Sewage system type (open, closed), distance, cost | MOH/Local mapping | (116) |
| Distance to sewage system access | Meters | Rainfall, slope/terrain, manholes, sewage system type (open, closed) | MOH/Local mapping | (114, 129) |

MOH, Ministry of Health.
Multiple studies included relied on surveillance data which did not correct for selection bias. Multiple studies included did not control for variables possibly associated with both exposure (trash) and outcome (disease), for example, socio-economic status (SES), access to health care, or climate. The data needed to understand the context-specific risk factors are not yet available; particularly, the authors noted a paucity of data from sub-Saharan Africa, where policies and regulations have recently been established (29). Interestingly, although geography was not constrained in the review, most studies identified were from low- and middle-income tropical countries.

After completing our search, we constrained the scope to only urban zoonosis associated with wild mammals and domesticated animals of non-agricultural interest such as dogs and cats. This may exclude some important research related to geographical areas where cows or other domestic animals can serve as crucial reservoirs of important etiological agents.

CONCLUSIONS

Despite gaps in the research base—lack of standardized measures and residual confounding—it is clear solid wastes breed vector-borne diseases and urban zoonoses.

Future populations are at increased risk—disease epidemics are increasing in scope and scale (42) with urban populations growing (38, 45), climate change providing newly suitable vector climates (39–41), and naive populations becoming newly at risk, sustainable solid waste management is crucial to prevention, specifically in urban environments that favor urban vectors such as *Aedes* species and in poor urban and rural populations which lack access to municipal solid waste services.

We propose a framework for solutions-based research which includes upstream innovation research, upstream policy, and downstream education to decrease demand for single-use plastics.

AUTHOR CONTRIBUTIONS

JF, AK, FM, and AL conceived of the initial idea and secured funding. AK drafted the initial manuscript. AK and GN conducted the literature search. LO and AL provided editing on intellectual content. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2019.00405/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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