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Review article

A systematic review of animal feeding operations including concentrated animal feeding operations (CAFOs) for exposure, health outcomes, and environmental justice

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ABSTRACT

Background: Despite growing literature on animal feeding operations (AFOs) including concentrated animal feeding operations (CAFOs), research on disproportionate exposure and associated health burden is relatively limited and shows inconclusive findings.
Objective: We systematically reviewed previous literature on AFOs/CAFOs, focusing on exposure assessment, associated health outcomes, and variables related to environmental justice (EJ) and potentially vulnerable populations.
Methods: We conducted a systematic search of databases (MEDLINE/PubMed and Web of Science) and performed citation screening. Screening of titles, abstracts, and full-text articles and data extraction were performed independently by pairs of reviewers. We summarized information for each study (i.e., study location, study period, study population, study type, study design, statistical methods, and adjusted variables (if health association was examined), and main findings), AFO/CAFO characteristics and exposure assessment (i.e., animal type, data source, measure of exposure, and exposure assessment), health outcomes or symptoms (if health association was examined), and information related to EJ and potentially vulnerable populations (in relation to exposure and/or health associations, vulnerable populations considered, related variables, and main findings in relation to EJ and vulnerable populations).
Results: After initial screening of 10,963 papers, we identified 76 eligible studies. This review found that a relatively small number of studies (20 studies) investigated EJ and vulnerability issues related to AFOs/CAFOs exposure and/or associated health outcomes (e.g., respiratory diseases/symptoms, infections). We found differences in findings across studies, populations, the metrics used for AFO/CAFO exposure assessment, and variables related to EJ and vulnerability. The most commonly used metric for AFO/CAFO exposure assessment was presence of or proximity to facilities or animals. The most investigated variables related to disparities were race/ethnicity and socioeconomic status.
Conclusion: Findings from this review provide suggestive evidence that disparities exist with some subpopulations having higher exposure and/or health response in relation to AFO/CAFO exposure, although results varied across studies.

1. Introduction

Large-scale intensive livestock production in the United States has grown substantially over the past few decades (USDA, 2019). These industrial-scale farms including concentrated animal feeding operations (CAFOs) generate various negative impacts on environments and human health hazards for workers and surrounding communities. Several studies reported that environmental detriments such as harmful airborne emissions (e.g., ammonia, hydrogen sulfide, particulate matter, endotoxins), poor soil and water quality (e.g., contaminated soil, surface water, and ground water with harmful pathogens, antibiotics, and heavy metals), and odors emitted from large amounts of animal waste may affect human health (e.g., risk of respiratory disease, infection,

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Abbreviations

AFOs	Animal feeding operations
CAFOs	Concentrated animal feeding operations
EJ	Environmental justice
NHB	Non-Hispanic Black
PM	Particulate matter
SES	Socioeconomic status

waterborne illness, vector-borne disease) and quality of life for farm workers and populations living near CAFOs (Heederik et al., 2007; Mitloehner and Schenker, 2007; O'Connor et al., 2017). For example, contaminated soil and water quality can affect crop quality and food safety and contaminated food products such as meat and dairy can lead to foodborne illness (Burkholder et al., 2007; Martínez et al., 2020).

Disparities regarding exposure to AFOs/CAFOs and the subsequent health burdens are of great concern, especially as some studies have found disproportionate siting of AFOs/CAFOs in disadvantaged communities such as those with a high fraction of racial/ethnic minority persons or those with low socioeconomic status (SES). Some studies on environmental justice have investigated disproportionate CAFOs exposure and associated health burdens among populations living near CAFOs, however the evidence is limited and the results are inconclusive (Carrel et al., 2016; Galarraga et al., 2022; Holcomb et al., 2022; Quist et al., 2022; Son et al., 2021a, 2021b; Son and Bell, 2022, 2023). Furthermore, studies used several different variables related to environmental justice to reflect various aspects of environmental injustice, however findings on disadvantaged communities vary by location and the environmental justice and related variables used in the study.

Although studies on AFOs/CAFOs have used various approaches to estimate population's exposure to AFOs/CAFOs, capturing multi-faceted environmental exposures is challenging due to the complexities of AFOs/CAFOs exposure through multiple pathways. Many studies commonly applied useful but simplistic methods of a binary indicator for the presence (or absence) of a facility within a given spatial area (e.g., county or ZIP code) to reflect proximity to the facility, however, more precise exposure assessment is needed to evaluate environmental disparities from AFOs/CAFOs exposure and associated health burden given the limitations of such approaches. The inconsistent findings in previous studies may result from differences in exposure assessment and other methodologies, populations, or AFO/CAFO characteristics, thus synthesizing the scientific evidence is critical to inform and identify research needs and directions for future studies on AFOs/CAFOs exposure and environmental justice as well as policies and strategies to address the health burden of AFOs/CAFOs, especially for vulnerable communities.

In this study, we systematically reviewed previous literature on exposure to AFOs/CAFOs and the associated health effects. We focused on AFOs/CAFOs exposure assessment, health outcomes and symptoms associated with AFO/CAFO exposure, and variables related to environmental justice and potentially vulnerable and susceptible populations. We conducted a systematic search by first identifying potential studies using a specified protocol on search terms related to AFO/CAFO exposure. Then title/abstract screening and subsequently full-text screening were conducted by pairs of reviewers independently using a priori inclusion criteria. We then extracted information (e.g., study characteristics, exposure assessment, health outcomes, variables related to environmental justice and potentially vulnerable populations) from each eligible study based on pre-formatted form. We presented findings qualitatively by summarizing results based on several criteria. For example, we provided summary findings of environmental justice and vulnerable populations from all relevant studies to present current evidence on the disproportionate exposure to AFOs/CAFOs and associated health burden. These findings can inform knowledge gaps and help identify critical research needs and direction for future study on environmental justice regarding AFOs/CAFOs exposure and the subsequent health burdens.

2. Methods

2.1. Systematic search strategy

We conducted a systematic search using a MEDLINE/PubMed, Web of Science databases for population-based studies of exposure to AFO/CAFO through March 14, 2023. We searched literature using terms related to AFO/CAFO exposure to identify relevant papers. To broadly capture AFO/CAFO-related papers, first, we used only AFO/CAFO-related terms for the search. We then screened the papers for exposure and/or health associations at the later stages. The search terms were as follows.

- Search terms: "CAFO" or "CAFOs" or "AFO" or "AFOs" or "concentrated animal feeding operation" or "concentrated animal feeding operations" or "animal feeding facility" or "animal feeding facilities" or "animal feeding operation" or "animal feeding operations" or "confined animal feeding operation" or "confined animal feeding operations" or (waste and lagoon*) or "animal waste" or "animal wastes" or "livestock waste" or "livestock wastes"

where * indicates any combination of subsequent letters.

To include additional relevant studies that may not retrieved by the electronic database searches, we performed citation screening and manually reviewed the reference lists from studies identified as eligible for this review after full-text screening. The systematic search was conducted with consideration of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines (Moher et al., 2015).

2.2. Selection criteria for eligible studies

We selected studies meeting the following inclusion criteria. Studies had to (1) consider exposure to AFO/CAFO and investigate exposure for human populations; (2) be peer-reviewed; and (3) be written in English. We included studies that investigated any measure of exposure to AFO/CAFO (e.g., distance from the nearest facility, endotoxin levels). This review was limited to population-based studies, excluding other study designs (e.g., animal or toxicology studies). Studies that assessed the environmental impacts and intermediate steps of AFO/CAFO exposure (e.g., studies investigating water quality but not people's exposure to water quality) were excluded. Non-research articles including reviews, commentaries, editorials, workshop report, and books were excluded.

The selection of studies included a two-stage screening of the articles (i.e., first stage: title and abstract, second stage: full-text review). Each stage of screening was performed independently by pairs of reviewers (two reviewers among JYS, SH, GB, DF, YS, BML, RS, HMC, and MLB). Inconsistencies between reviewers were resolved by a third reviewer (JYS or MLB). After screening, data extraction was performed by pairs of reviewers (among JYS, SH, GB, DF, YS, BML, RS, and HMC) independently based on pre-formatted form. Any discrepancies in data extraction were resolved by the first author (JYS). The following information was extracted from each article: (1) study information including study location, study period, study population, study type (i.e., examined exposure only, examined both exposure and health associations), study design, statistical methods, and adjusted variables (if health association was examined), and main findings; (2) characteristics regarding AFO/CAFO exposure including animal type of AFO/CAFO, data source (e.g., government or state database, personal air monitoring, satellite data), measure of exposure (e.g., air pollution level, endotoxin level, water quality, odor severity, presence/proximity of facility), and exposure assessment (metrics used to define the exposure, e.g., daily average ammonia concentration, CAFO density within ZIP code, distance between hog CAFO and census block centroid); (3) health outcomes or symptoms (if health association was examined) including physical, mental, and social well-being; and (4) information related to environmental justice and potentially vulnerable populations including in relation to exposure and/or health associations, vulnerable populations examined in the study (e.g., racial/ethnic minority populations, persons with low SES, immigrants), related variables (e.g., percentage of non-Hispanic Black (NHB), percentage of people living below the poverty level, median annual household income), and main findings in relation to environmental justice and vulnerable populations. We focused on findings identified by authors regardless of statistical significance.

Environmental justice refers to the disproportionate health burden suffered by some subpopulations from environmental exposure, such as for racial/ethnic minority persons or those with low SES. Here we refer to environmental justice and related variables broadly to include those in studies that specified "environmental justice" concerns and those that examined characteristics (e.g., percent of the population that is Hispanic) of potentially vulnerable populations to evaluate if some persons had higher exposure to AFOs/CAFOs or higher health response from exposure to AFOs/CAFOs.

We qualitatively summarized the findings from the literature review. While meta-analysis is frequently applied in systematic reviews to estimate overall findings from individual studies, we did not conduct meta-analysis due to lack of sufficient number of studies with the same category (e.g., same health outcomes/symptoms) for studies examining health associations. We provided detailed information for each study (e.g., study location, period, population, data sources, exposure and exposure assessment, animal type of AFO/CAFO, health outcomes/symptoms, study design, statistical model, adjusted variables, and main findings and authors' conclusions). For studies that examined environmental justice and disparity issues, we reported detailed information on disparities in exposure and/or health associations, the subpopulations examined, related variables, and main findings in relation to EJ and disparity. We summarized findings using frequency and proportion of articles by study characteristics based on several criteria (e.g., study information, AFO/CAFO characteristics and exposure assessment, and environmental justice and vulnerable populations).

3. Results

3.1. Summary of study characteristics

A total of 10,963 papers were identified through database searching. After duplicates were removed, 8813 unique papers were initially screened, and 8713 papers were excluded from the title and abstract screening. The full-text screening of the remaining 100 papers resulted in 64 eligible studies for inclusion in this review and an additional 12 eligible papers were included through the citation screening (Fig. 1). The excluded studies were not population-based, non-research, did not investigate the exposure of interest, or examined AFO/CAFO exposure

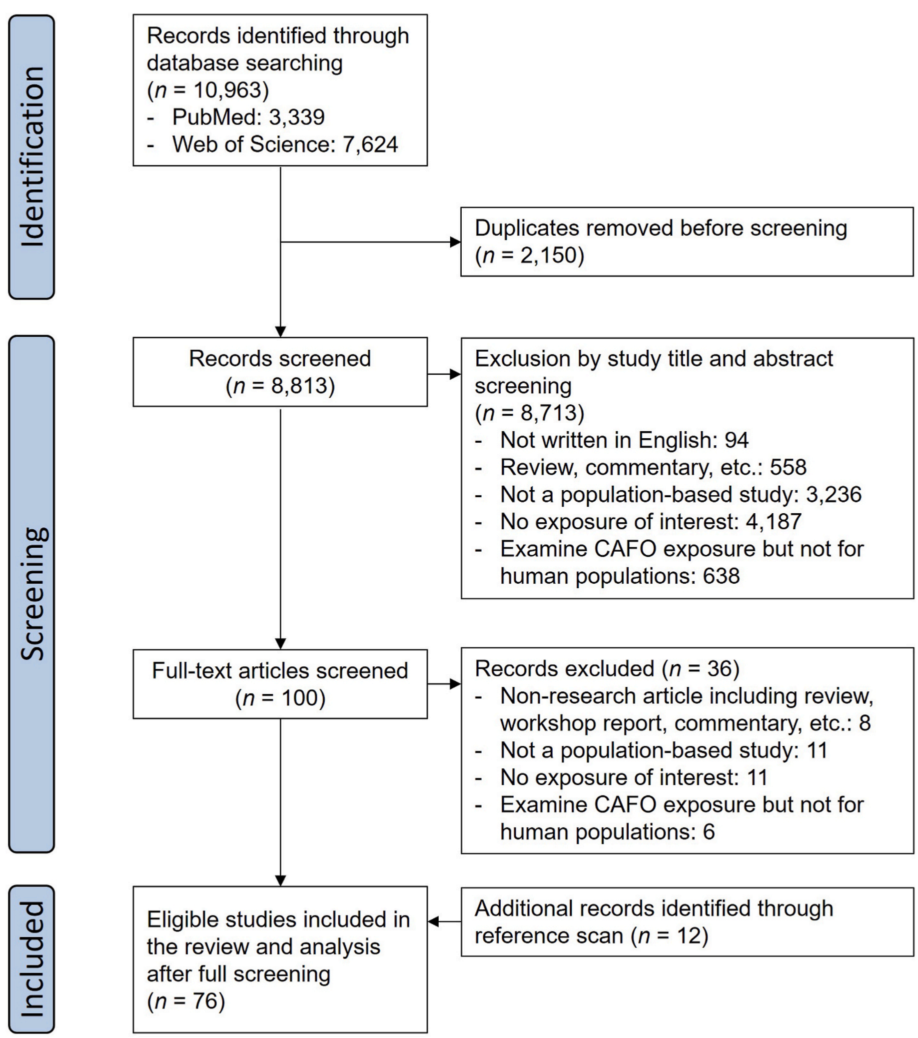

Fig. 1. Flow diagram of literature selection process for systematic review.

but not for human populations.

Table S1 provides the characteristics of the 76 studies included in this review. Twenty-two studies examined exposure only and 54 studies assessed the association between AFO/CAFO exposure and health outcomes. For exposure only studies, we summarized characteristics based on study location and period, study population, measure of exposure, data source, animal type of AFO/CAFO, exposure assessment, whether the study examined environmental justice issues, and main findings. For studies investigating associations between AFO/CAFO exposure and health outcomes, we included additional information on health outcomes/symptoms, study design, adjusted variables, and statistical methods.

Table 1 and Fig. 2 provide summary characteristics of the 76 studies included in this review. Most studies were conducted in the United States (US) (60.5%), published between 2016 and 2020 (43.4%), and examined associations between exposure and health outcomes (71.1%). Among the 76 studies, 20 studies investigated issues of vulnerable populations and environmental justice. Of these 20 studies, 13 evaluated exposure disparity. Of the 54 studies that examined health associations, respiratory diseases/symptoms were the most commonly considered outcome (26 studies), followed by infections (20 studies). Most studies used cross-sectional study design (41 studies).

Fig. 3 shows spatial distribution of published AFO/CAFO studies across the World and those within the US. The most represented country was the United States (46 studies), followed by the Netherlands (18 studies). Among the 46 studies conducted in the US, the most investigated state was North Carolina (15 studies), followed by Iowa (8 studies).

3.2. Summary of exposure assessment

Characteristics of the identified exposure assessment studies are presented in Table 2. Many studies considered swine (57 studies), cattle (42 studies), and/or poultry (40 studies) CAFOs. Other animal types of AFO/CAFO were goat/sheep (21 studies) and others (e.g., mink, horses) (19 studies). Most studies used government or state database (56 studies) as a data source to estimate exposure to AFOs/CAFOs. Other studies used data from various sources such as survey, air pollution modeling, personal air monitoring, sampling, and satellite data. As a proxy of AFO/CAFO exposure, various measures were used. Many studies used multiple measures (e.g., ammonia and endotoxin levels, odor and proximity) to estimate the AFO/CAFO exposure. Exposure to AFOs/CAFOs includes many aspects of the facilities such as water quality, air pollution, noise, and odor. Rather than assess each of these or a subset, many studies consider distance to AFOs/CAFOs or density of AFOs/CAFOs (number of facilities in a given area) to assess exposure. The most used measure for AFO/CAFO exposure was presence of or proximity to a facility or specific farm animals within some boundaries or buffers (37 studies), followed by density (34 studies) and air pollution (27 studies). Other studies applied several measures such as amount of animal waste, odor severity, and water quality to estimate the exposure to AFOs/CAFOs. Exposure assessment for each measure varied across studies. Many studies assessed AFO/CAFO exposure using the number of animals, animal units, or farms for a given area (e.g., per square mile, within a specified buffer) (32 studies). Other studies considered distance to the nearest facility (22 studies); presence of facility or specific farm animal within administrative boundaries such as county, census tract, ZIP code or specific buffers (21 studies); air pollution assessed through monitors or modeled exposure (20 studies); and other approaches (e.g., odor annoyance, bacteria concentration in groundwater sample).

3.3. Summary of evidence for findings on environmental justice and vulnerable populations

Table S2 summarizes findings on the environmental justice and vulnerable populations and related variables from each of the 20 studies

Table 1
Summary of study characteristics for the 76 studies included in this review.

Criterion	Number of Studies (%)	Reference
Study location		
US	46 (60.5%)	Carrel et al. (2016); Donham et al., 2006; Galarraga et al. (2022); Garcia et al., 2013; Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Pavilonis et al. (2013); Son et al. (2021a); Williams et al., 2011; Wilson et al. (2002); Wilson and Serre, 2007; Wing et al. (2000); Ayala-Ramirez et al. (2023); Beresin et al., 2017; Booth et al., 2017; Carrel et al. (2014); Fisher et al. (2020); Goldstein et al. (2016); Hatcher et al. (2017); Hill et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Jagai et al., 2010; Kanankege et al., 2023; Kravchenko et al. (2018); Kravchenko et al. (2020); Loftus et al., 2015; Loftus et al., 2020; Mendrinos et al. (2022); Merchant et al., 2005; Mirabelli et al. (2006b); Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Poulsen et al. (2018); Quist et al. (2022); Rasmussen et al. (2017); Schinasi et al., 2014; Schultz et al. (2019); Shaw et al. (2016); Sigurdarson et al., 2006; Sneeringer, 2009; Son et al. (2021b)
Non-US	30 (39.5%)	Blanes-Vidal et al., 2012; Boers et al., 2016; Douglas et al. (2021); McDonnell et al., 2008; Pham-Duc et al., 2020; Pohl et al., 2017; Wu et al., 2020; Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Hanif and Martini, 2019; Hooiveld et al., 2015; Hooiveld et al. (2016); Kiss et al. (2023); Michalopoulos et al., 2016; Müller-Rompa et al., 2018; Radon et al., 2007; Schulze et al., 2011; Smit et al. (2014); Smit et al. (2012); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020; van Kersen et al. (2022)
Publication year		
≤2005	4 (5.3%)	Wilson et al. (2002); Wing et al. (2000); Hill et al., 2005; Merchant et al., 2005
2006–2010	10 (13.2%)	Donham et al., 2006; McDonnell et al., 2008; Mirabelli et al. (2006a); Wilson and Serre, 2007; Hill et al., 2006; Jagai et al., 2010; Mirabelli et al. (2006b); Radon et al., 2007; Sigurdarson et al., 2006; Sneeringer, 2009
2011–2015	15 (19.7%)	Blanes-Vidal et al., 2012; Garcia et al., 2013; Lenhardt and Ogneva-Himmelberger (2013); Ogneva-Himmelberger et al. (2015); Pavilonis et al. (2013);

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Table 1 (*continued*)

Criterion	Number of Studies (%)	Reference
		Williams et al., 2011; Borlée et al. (2015); Carrel et al. (2014); Hooiveld et al., 2015; Loftus et al., 2015; Pavilonis et al. (2013); Schinasi et al., 2014; Schulze et al., 2011; Smit et al. (2014); Smit et al. (2012)
2016–2020	33 (43.4%)	Boers et al., 2016; Carrel et al. (2016); Pham-Duc et al., 2020; Pohl et al., 2017; Wu et al., 2020; Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2017); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Hanif and Martini, 2019; Hatcher et al. (2017); Hooiveld et al. (2016); Kravchenko et al. (2018); Kravchenko et al. (2020); Loftus et al., 2020; Michalopoulos et al., 2016; Müller-Rompa et al., 2018; Murray et al. (2020); Poulsen et al. (2018); Rasmussen et al. (2017); Schultz et al. (2019); Shaw et al. (2016); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020
≥2021	14 (18.4%)	Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Son et al. (2021a); Ayala-Ramirez et al. (2023); Holcomb et al. (2022); Kanankege et al., 2023; Kiss et al. (2023); Mendrinos et al. (2022); Murray et al. (2021); Quist et al. (2022); Son et al. (2021b); van Kersen et al. (2022)
Study type		
Examined exposure only	22 (28.9%)	Blanes-Vidal et al., 2012; Boers et al., 2016; Carrel et al. (2016); Donham et al., 2006; Douglas et al. (2021); Galarraga et al. (2022); Garcia et al., 2013; Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); McDonnell et al., 2008; Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Pavilonis et al. (2013); Pham-Duc et al., 2020; Pohl et al., 2017; Son et al. (2021a); Williams et al., 2011; Wilson et al. (2002); Wilson and Serre, 2007; Wing et al. (2000); Wu et al., 2020
Examined exposure and health associations	54 (71.1%)	Ayala-Ramirez et al. (2023); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Hanif and Martini, 2019; Hatcher et al. (2017); Hill et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kiss et al. (2023); Kravchenko et al. (2018); Kravchenko et al. (2020); Loftus et al., 2015; Loftus et al., 2020; Mendrinos et al. (2022); Merchant et al., 2005; Michalopoulos et al., 2016; Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Poulsen et al. (2018); Quist et al. (2022); Radon et al., 2007; Rasmussen et al. (2017); Schinasi et al., 2014; Schultz et al. (2019); Schulze et al., 2011; Shaw et al. (2016); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020; van Kersen et al. (2022)
Examined issues of EJ/differences by subpopulation		
Yes	20 (26.3%)	Carrel et al. (2016); Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Son et al. (2021a); Wilson et al. (2002); Wing et al. (2000); Ayala-Ramirez et al. (2023); Fisher et al. (2020); Hatcher et al. (2017); Holcomb et al. (2022); Hooiveld et al. (2016); Kravchenko et al. (2018); Kravchenko et al. (2020); Quist et al. (2022); Son et al. (2021b)
No	56 (73.7%)	Blanes-Vidal et al., 2012; Boers et al., 2016; Donham et al., 2006; Garcia et al., 2013; McDonnell et al., 2008; Pham-Duc et al., 2020; Pohl et al., 2017; Pavilonis et al. (2013); Williams et al., 2011; Wilson and Serre, 2007; Wu et al., 2020; Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Goldstein et al. (2016); Hanif and Martini, 2019; Hill et al., 2005; Hill et al., 2006; Hooiveld et al., 2015; Jagai et al., 2010; Kanankege et al., 2023; Kiss et al. (2023); Loftus et al., 2015; Loftus et al., 2020; Mendrinos et al. (2022); Merchant et al., 2005; Michalopoulos et al., 2016; Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Poulsen et al. (2018); Radon et al., 2007; Rasmussen et al. (2017); Schinasi et al., 2014; Schultz et al. (2019); Schulze et al., 2011; Shaw et al. (2016); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009;

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Table 1 (*continued*)

Criterion	Number of Studies (%)	Reference
		Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020; van Kersen et al. (2022)
Of the 20 EJ/vulnerability studies, examined in relation to		
Exposure only	13 (65.0%)	Carrel et al. (2016); Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Son et al. (2021a); Wilson et al. (2002); Wing et al. (2000); Fisher et al. (2020); Kravchenko et al. (2018)
Health associations only	5 (25.0%)	Ayala-Ramirez et al. (2023); Hatcher et al. (2017); Hooiveld et al. (2016); Kravchenko et al. (2020); Quist et al. (2022)
Both exposure and health associations	2 (10.0%)	Holcomb et al. (2022); Son et al. (2021b)
Health outcomes/symptoms[a]		
Respiratory diseases/symptoms (e.g., asthma, COPD) or lung function (e.g., FEV_1, FVC, PEF)	26	Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Hooiveld et al., 2015; Hooiveld et al. (2016); Kiss et al. (2023); Loftus et al., 2015; Loftus et al., 2020; Merchant et al., 2005; Michalopoulos et al., 2016; Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Pavilonis et al. (2013); Radon et al., 2007; Rasmussen et al. (2017); Schultz et al. (2019); Schulze et al., 2011; Sigurdarson et al., 2006; Smit et al. (2014); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020
Immune-mediated diseases (e.g., rheumatoid arthritis, hypothyroidism, HIV)	8	Ayala-Ramirez et al. (2023); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Borlée et al. (2018); Kanankege et al., 2023; Müller-Rompa et al., 2018; Radon et al., 2007
Infections (e.g., Campylobacteriosis, gastrointestinal illness, MRSA)	20	Beresin et al., 2017; Carrel et al. (2014); Goldstein et al. (2016); Hill et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kravchenko et al. (2018); Loftus et al., 2020; Michalopoulos et al., 2016; Murray et al. (2020); Murray et al. (2021); Poulsen et al. (2018); Quist et al. (2022); Schinasi et al., 2014; Shaw et al. (2016); Smit et al. (2012); Van Dijk et al. (2017)
Mortality	5	Kanankege et al., 2023; Kravchenko et al. (2018); Kravchenko et al. (2020); Sneeringer, 2009; Son et al. (2021b)
Birth outcomes (e.g., preterm birth, low birth weight)	4	Kanankege et al., 2023; Kravchenko et al. (2018); Mendrinos et al. (2022); Sneeringer, 2009
Cancer	5	Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Booth et al., 2017; Fisher et al. (2020)
Gastrointestinal symptoms (e.g., diarrhea, stomachache, nausea)	3	Baliatsas et al., 2020; Hanif and Martini, 2019; Hooiveld et al., 2015
Neurological symptoms (e.g., headache, dizziness)	5	Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Hooiveld et al., 2015; Van Dijk et al. (2017)
Mental health, quality of life	6	Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Hooiveld et al., 2015; Michalopoulos et al., 2016; Van Dijk et al. (2017)
Blood disorder (e.g., anemia, septicemia, hyperlipidemia)	4	Baliatsas et al. (2017); Baliatsas et al. (2019); Kanankege et al., 2023; Kravchenko et al. (2018)
Kidney disease	2	Kanankege et al., 2023; Kravchenko et al. (2018)
Endocrine disease (e.g., diabetes)	3	Baliatsas et al. (2017); Baliatsas et al. (2019); Kanankege et al., 2023
Digestive disorder	2	Baliatsas et al. (2017); Baliatsas et al. (2019)
Cardiovascular disease (e.g., heart failure, coronary heart disease, hypertension)	3	Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020
Bone disease	2	Baliatsas et al. (2017); Baliatsas et al. (2019)
Others	3	Borkenhagen et al. (2020); Hatcher et al. (2017); van Kersen et al. (2022)
Study design[b]		
Longitudinal, cohort, panel	7 (13.0)	Ayala-Ramirez et al. (2023); Borkenhagen et al. (2020); Fisher et al. (2020); Loftus et al., 2015; Loftus et al., 2020; Van Dijk et al. (2016a); van Kersen et al., 2020
Case-control	6 (11.1)	Baliatsas et al., 2020; Poulsen et al. (2018); Rasmussen et al. (2017); Schinasi et al., 2014; Van Dijk et al. (2017); van Kersen et al. (2022)
Ecological, cross-sectional	41 (75.0)	Baliatsas et al. (2017); Baliatsas et al. (2019); Beresin et al., 2017; Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Goldstein et al. (2016); Hanif and Martini, 2019; Hatcher et al. (2017); Hill et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kiss et al. (2023); Kravchenko et al. (2018); Kravchenko et al. (2020); Mendrinos et al. (2022); Merchant et al., 2005; Michalopoulos et al., 2016; Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Quist et al. (2022); Radon et al., 2007; Schultz et al. (2019); Schulze et al., 2011; Shaw et al. (2016); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016b)

Notes: Respiratory diseases/symptoms (e.g., asthma, COPD, wheezing, dyspnea, shortness of breath, nasal allergy, allergic rhinitis, upper respiratory tract infections) or lung function (e.g., FEV_1, FVC, PEF); Immune-mediated diseases (e.g., rheumatoid arthritis, hypothyroidism, HIV, allergy, allergen-specific immunoglobulin E (IgE) measurements, eczema); Infections (e.g., Campylobacteriosis, gastrointestinal illness, UTI, tuberculosis, biomarker of systemic inflammation, allergic rhinitis); Mental health, stress related symptoms (e.g., fatigue, sleeping problems, anxiousness, depression), quality of life; Others (e.g., oropharyngeal microbiota (OPM) composition, antibiotic-resistant (ABR) *S. aureus* nasal carriage prevalence, Seroconversion against swine influenza A viruses (H1N1 and H3N2) infection).

Abbreviations: COPD (chronic obstructive pulmonary disease), EJ (environmental justice), FEV_1 (forced expiratory volume), FVC (forced vital capacity), PEF (peak expiratory flow), HIV (human immunodeficiency virus), MRSA (methicillin-resistant *Staphylococcus aureus*).

[a] Health outcomes/symptoms: exposure and health outcomes studies (n = 54) only; Some studies contributed more than one result and are represented in multiple rows.

[b] Study design: exposure and health outcomes studies (n = 54) only.

that investigated these issues in relation to exposure and/or health associations. Thirteen studies evaluated environmental justice and vulnerability in relation to exposure, 5 studies in relation to health associations, and 2 studies in relation to both exposure and health associations. Many studies considered race/ethnicity and SES with variables such as poverty, education, median household income, deprivation, health insurance status, homeownership, and school lunch enrollment. Other variables related to subpopulations considered in the studies were age, sex, immigrant status, health behavior, urban/rural classification, and residential isolation index.

Table 3 provides a summary of evidence for the findings on environmental justice and vulnerable populations in relation to AFOs/CAFOs. The most examined vulnerable population was people with low SES (18 studies with 14 that examined disparities by exposure and 4 studies that examined disparity by health response to AFO/CAFO exposure). Many studies reported disparities in exposure with higher AFO/CAFO exposure in those with lower SES (based on median household income, percentage of people living in poverty, low education, insurance status (publicly insured or uninsured), school lunch enrollment, educational isolation, number of primary care givers, or deprivation measures). Studies investigating health associations reported higher disparities in health response with higher AFO/CAFO exposure in those with lower SES (based on median household income, insurance status). However, some studies found no association or higher health effect from AFO/CAFO exposure in those with higher SES based on education, insurance status, and median household income. Of the 20 studies, 18 studies examined race/ethnicity (13 studies in relation to exposure, 5 studies in relation to health association). They found evidence of higher exposure and/or higher health response to AFO/CAFO exposure for people of color (e.g., NHB, American Indian, Asian), Hispanic persons, and communities with higher residential isolation for NHB. On the other hand, some studies found the opposite (i.e., lower association) or no association for people of color. Seven studies examined urbanicity/rurality in relation to vulnerability and reported higher disparities in exposure and/or health association in rural areas (3 studies) or urban areas (2 studies), and two studies found no association with population density or rurality. Two studies investigated both disparities in exposure and health associations and showed mixed findings. For example, a study in North Carolina, US found higher estimated mortality risk from CAFOs for some subpopulations such as non-Hispanic White, people with higher SES, although the areas with higher CAFOs exposure had higher percentages of NHB and people with low SES compared to the areas without CAFO exposure (Son et al.,

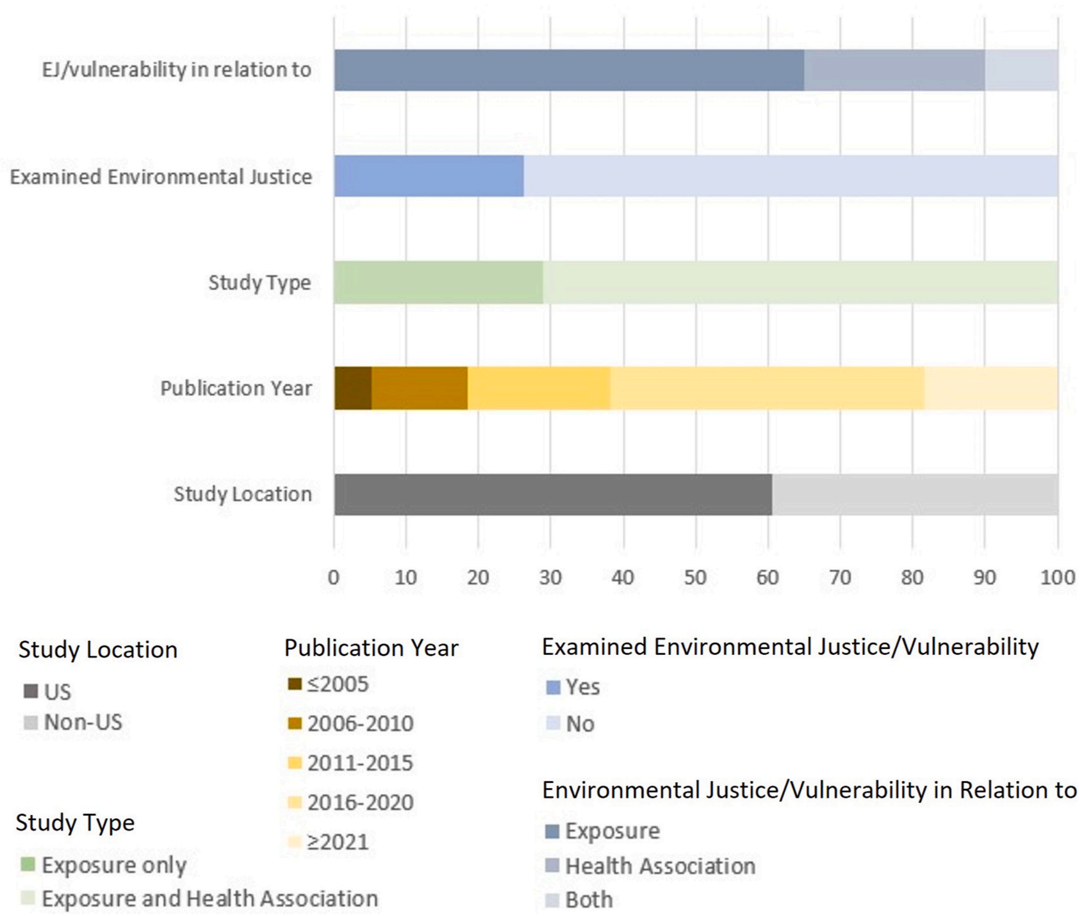

Fig. 2. Summary of study characteristics.

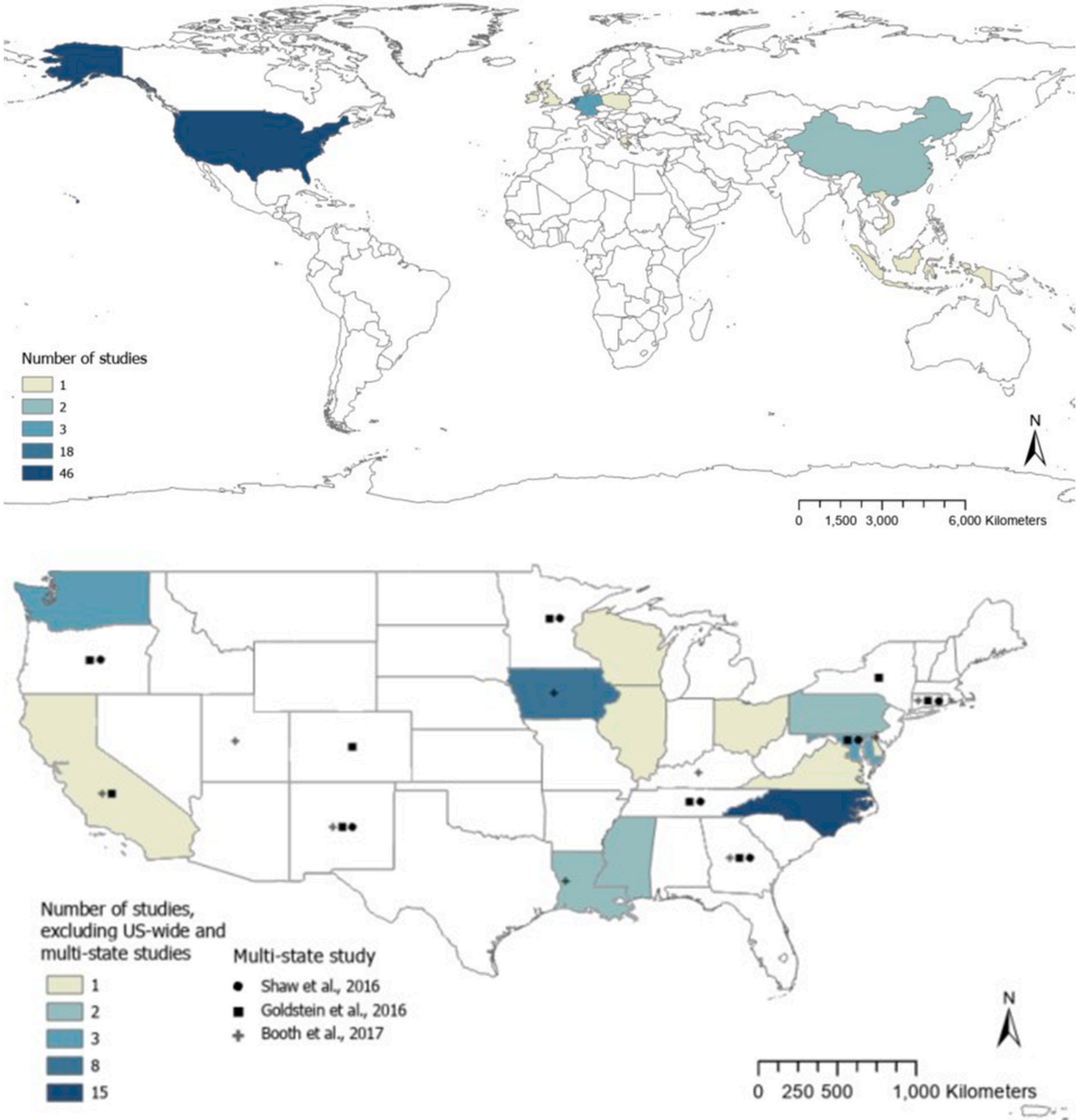

Fig. 3. Spatial distribution map of published AFO/CAFO studies (A) in the world and (B) across US states.
Note: For Fig. 3(A), the included countries are US, Netherlands, Germany, China, Ireland, Poland, Vietnam, United Kingdom, Denmark, Greece, and Indonesia. For Figs. 3(B) and 2 studies investigated the entire US (Jagai et al., 2010; Sneeringer, 2009) and 3 were multi-state studies (Booth et al., 2017 (9 US states: CA, CT, GA, IA, KY, LA, NJ, NM, UT); Goldstein et al., 2016 (10 US states: CT, GA, MD, MN, NM, OR, TN, CA, CO, NY); Shaw et al., 2016 (7 US states: CT, GA, MD, MN, NM, OR, TN)). Each symbol represents a multi-state study. The US-wide studies were not included in Fig. 3(B).
Sixteen studies were state level (Carrel et al., 2016; Galarraga et al., 2022; Hall et al., 2021; Khanjar et al., 2022; Lenhardt and Ogneva-Himmelberger, 2013; Son et al., 2021a; Wilson et al., 2002; Wing et al., 2000; Beresin et al., 2017; Hill et al., 2005; Hill et al., 2006; Holcomb et al., 2022; Murray et al., 2020; Murray et al., 2021; Quist et al., 2022; Son et al., 2021b) in Fig. 3(B) across US states.

2021b). Other studies considered age with higher exposure and associated health effect from AFO/CAFO exposure in younger or older populations. Three studies found higher health response in females, with one study finding higher health effect in males and one with no association by sex. Two studies considered health behavior with higher health effect in smokers and no exposure disparity with smoking status or alcohol use. Two studies considered foreign born status, with one finding lower CAFO exposure in foreign born populations compared to native-born persons, whereas the other study reported no association.

4. Discussion

This study systematically reviewed previous literature on exposure to AFOs/CAFOs and the associated health effects. We evaluated AFOs/CAFOs exposure assessment, health outcomes and symptoms associated with AFO/CAFO exposure, and environmental justice related variables and potentially vulnerable and susceptible populations.

This systematic review found that a relatively small number of studies have investigated environmental justice and vulnerability issues related with AFOs/CAFOs exposure and/or associated health outcomes.

Table 2
Summary of AFO/CAFO characteristics and exposure assessment.

Criterion	Number of studies	Reference
Animal type of AFO/CAFO		
Swine	57	Blanes-Vidal et al., 2012; Boers et al., 2016; Carrel et al. (2016); Donham et al., 2006; Douglas et al. (2021); Lenhardt and Ogneva-Himmelberger (2013); McDonnell et al., 2008; Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Pavilonis et al. (2013); Pham-Duc et al., 2020; Son et al. (2021a); Wilson et al. (2002); Wilson and Serre, 2007; Wing et al. (2000); Ayala-Ramirez et al. (2023); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Fisher et al. (2020); Hatcher et al. (2017); Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Kanankege et al., 2023; Kiss et al. (2023); Kravchenko et al. (2018); Kravchenko et al. (2020); Merchant et al., 2005; Michalopoulos et al., 2016; Mirabelli et al. (2006b); Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Quist et al. (2022); Radon et al., 2007; Rasmussen et al. (2017); Schinasi et al., 2014; Schultz et al. (2019); Shaw et al. (2016); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Poultry	40	Boers et al., 2016; Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); Pohl et al., 2017; Son et al. (2021a); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Hill et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Kiss et al. (2023); Loftus et al., 2015; Mendrinos et al. (2022); Murray et al. (2020); Murray et al. (2021); Poulsen et al. (2018); Radon et al., 2007; Schultz et al. (2019); Shaw et al. (2016); Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Cattle	42	Blanes-Vidal et al., 2012; Boers et al., 2016; Douglas et al. (2021); Garcia et al., 2013; Lenhardt and Ogneva-Himmelberger (2013); Son et al. (2021a); Williams et al., 2011; Wu et al., 2020; Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Hanif and Martini, 2019; Hill et al., 2005; Hill et al., 2006; Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kiss et al. (2023); Loftus et al., 2015; Loftus et al., 2020; Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Radon et al., 2007; Rasmussen et al. (2017); Schultz et al. (2019); Shaw et al. (2016); Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Goat/sheep	21	Boers et al., 2016; Son et al. (2021a); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Fisher et al. (2020); Hooiveld et al. (2016); Kiss et al. (2023); Murray et al. (2020); Murray et al. (2021); Smit et al. (2014); Smit et al. (2012); Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Others (e.g., mink, horses)	19	Boers et al., 2016; Son et al. (2021a); Baliatsas et al. (2017); Baliatsas et al. (2019); Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Fisher et al. (2020); Kiss et al. (2023); Murray et al. (2020); Murray et al. (2021); Smit et al. (2014); Smit et al. (2012); Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Various types, others, not reported	4	Boers et al., 2016; Merchant et al., 2005; Schulze et al., 2011; van Kersen et al., 2020
Data source		
Government or state database (e.g., DEQ permit database, emission data)	56	Boers et al., 2016; Carrel et al. (2016); Donham et al., 2006; Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Lenhardt and Ogneva-Himmelberger (2013); McDonnell et al., 2008; Mirabelli et al. (2006a); Ogneva-Himmelberger et al. (2015); Pohl et al., 2017; Son et al. (2021a); Wilson et al. (2002); Wing et al. (2000); Baliatsas et al. (2017); Baliatsas et al. (2019); Baliatsas et al., 2020; Booth et al., 2017; Borlée et al. (2018); Borlée et al. (2015); Carrel et al. (2014); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Hill

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Table 2 (*continued*)

Criterion	Number of studies	Reference
		et al., 2005; Hill et al., 2006; Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kiss et al. (2023); Kravchenko et al. (2018); Kravchenko et al. (2020); Loftus et al., 2015; Mendrinos et al. (2022); Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Poulsen et al. (2018); Quist et al. (2022); Radon et al., 2007; Rasmussen et al. (2017); Schinasi et al., 2014; Schultz et al. (2019); Shaw et al. (2016); Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017)
Survey, questionnaire, or interview	10	Blanes-Vidal et al., 2012; Mirabelli et al. (2006a); Pham-Duc et al., 2020; Williams et al., 2011; Borkenhagen et al. (2020); Hanif and Martini, 2019; Hooiveld et al., 2015; Merchant et al., 2005; Radon et al., 2007; van Kersen et al., 2020
Air pollution modeling	6	Blanes-Vidal et al., 2012; Ogneva-Himmelberger et al. (2015); Wu et al., 2020; Müller-Rompa et al., 2018; Schulze et al., 2011; van Kersen et al. (2022)
Air quality monitoring, sampling	10	Blanes-Vidal et al., 2012; Garcia et al., 2013; Pavilonis et al. (2013); Williams et al., 2011; Wilson and Serre, 2007; Wu et al., 2020; Loftus et al., 2015; Loftus et al., 2020; Schulze et al., 2011; van Kersen et al., 2020
Other (e.g., wastewater sampling, satellite data, GIS database, estimated number of farms, animal density using simulator from national inventory data, calculated daily plume exposure based on factors, measurements of fly density)	7	Pham-Duc et al., 2020; Beresin et al., 2017; Hanif and Martini, 2019; Hatcher et al. (2017); Holcomb et al. (2022); Loftus et al., 2020; Müller-Rompa et al., 2018
Not reported	4	Ayala-Ramirez et al. (2023); Borlée et al. (2017); Michalopoulos et al., 2016; Sigurdarson et al., 2006
Exposure		
Air pollution (e.g., ammonia, carbon dioxide, $PM_{2.5}$, airborne endotoxin)	27	Blanes-Vidal et al., 2012; Donham et al., 2006; Garcia et al., 2013; Lenhardt and Ogneva-Himmelberger (2013); McDonnell et al., 2008; Ogneva-Himmelberger et al. (2015); Pavilonis et al. (2013); Pohl et al., 2017; Williams et al., 2011; Wilson and Serre, 2007; Wu et al., 2020; Baliatsas et al. (2017); Baliatsas et al. (2019); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Kiss et al. (2023); Loftus et al., 2015; Loftus et al., 2020; Müller-Rompa et al., 2018; Schulze et al., 2011; Smit et al. (2014); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al., 2020; van Kersen et al. (2022)

Table 2 (*continued*)

Criterion	Number of studies	Reference
Water quality[a]	2	Galarraga et al. (2022); Pham-Duc et al., 2020
Odor	6	Blanes-Vidal et al., 2012; Boers et al., 2016; Mirabelli et al. (2006a); Hooiveld et al., 2015; Radon et al., 2007; van Kersen et al., 2020
Presence/proximity of facility/specific farm animals within boundaries (e.g., county), buffer	37	Douglas et al. (2021); Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Mirabelli et al. (2006a); Ayala-Ramirez et al. (2023); Baliatsas et al. (2017); Baliatsas et al. (2019); Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Fisher et al. (2020); Goldstein et al. (2016); Kiss et al. (2023); Mendrinos et al. (2022); Michalopoulos et al., 2016; Mirabelli et al. (2006b); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Pavilonis et al. (2013); Poulsen et al. (2018); Quist et al. (2022); Rasmussen et al. (2017); Schultz et al. (2019); Shaw et al. (2016); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Density (number of animals/farms/animal units) within boundaries, buffer, km^2	34	Carrel et al. (2016); Lenhardt and Ogneva-Himmelberger (2013); Son et al. (2021a); Wilson et al. (2002); Wing et al. (2000); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kiss et al. (2023); Kravchenko et al. (2018); Kravchenko et al. (2020); Mendrinos et al. (2022); Poulsen et al. (2018); Quist et al. (2022); Radon et al., 2007; Schinasi et al., 2014; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Other[b]	7	Borkenhagen et al. (2020); Hanif and Martini, 2019; Hatcher et al., (2017); Hill et al., 2005; Hill et al., 2006; Merchant et al., 2005; Müller-Rompa et al., 2018
Exposure assessment		
Presence of facility/specific farm animals within boundary (e.g., county, census tract, ZIP code) or buffer	21	Galarraga et al. (2022); Hall et al. (2021); Khanjar et al. (2022); Baliatsas et al. (2017); Baliatsas et al. (2019); Borkenhagen et al. (2020); Borlée et al. (2015); Goldstein et al. (2016); Mendrinos et al. (2022); Müller-Rompa et al., 2018; Murray et al. (2020); Murray et al. (2021); Rasmussen et al. (2017); Shaw et al. (2016); Smit et al. (2014); Smit et al. (2012); Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b);

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Table 2 (*continued*)

Criterion	Number of studies	Reference
		Van Dijk et al. (2017); van Kersen et al. (2022)
Distance to the (nearest) facility, for a given area	22	Douglas et al. (2021); Galarraga et al. (2022); Mirabelli et al. (2006a); Ayala-Ramirez et al. (2023); Baliatsas et al. (2017); Baliatsas et al. (2019); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); de Rooij et al. (2019); Kiss et al. (2023); Michalopoulos et al., 2016; Mirabelli et al. (2006b); Pavilonis et al. (2013); Poulsen et al. (2018); Schultz et al. (2019); Sigurdarson et al., 2006; Smit et al. (2014); Smit et al. (2012); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017)
Modeled air pollution exposure (e.g., AERMOD dispersion model)	10	Blanes-Vidal et al., 2012; Donham et al., 2006; Ogneva-Himmelberger et al. (2015); Pohl et al., 2017; Wu et al., 2020; de Rooij et al. (2019); Kiss et al. (2023); Müller-Rompa et al., 2018; Smit et al. (2014); van Kersen et al. (2022)
Air quality monitoring, sampling	10	Blanes-Vidal et al., 2012; Garcia et al., 2013; McDonnell et al., 2008; Pavilonis et al. (2013); Williams et al., 2011; Wilson and Serre, 2007; Wu et al., 2020; Loftus et al., 2020; Schulze et al., 2011; van Kersen et al., 2020
Presence and concentration of antibiotic residues, bacteria, nitrate etc. in wells, wastewater, groundwater samples	2	Galarraga et al. (2022); Pham-Duc et al., 2020
Self-reported odor annoyance/ modeled odor exposure	6	Blanes-Vidal et al., 2012; Boers et al., 2016; Mirabelli et al. (2006a); Hooiveld et al., 2015; Radon et al., 2007; van Kersen et al., 2020
Number of animals/farms/ animal units/mile^2 or within buffer	32	Carrel et al. (2016); Lenhardt and Ogneva-Himmelberger (2013); Son et al. (2021a); Wilson et al. (2002); Wing et al. (2000); Baliatsas et al., 2020; Beresin et al., 2017; Booth et al., 2017; Borkenhagen et al. (2020); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Carrel et al. (2014); de Rooij et al. (2019); Holcomb et al. (2022); Hooiveld et al., 2015; Hooiveld et al. (2016); Jagai et al., 2010; Kanankege et al., 2023; Kravchenko et al. (2018); Kravchenko et al. (2020); Poulsen et al. (2018); Radon et al., 2007; Schinasi et al., 2014; Smit et al. (2014); Smit et al. (2012); Sneeringer, 2009; Son et al. (2021b); Van Dijk et al. (2016a); Van Dijk et al. (2016b); Van Dijk et al. (2017); van Kersen et al. (2022)
Inverse distance weighted air pollution levels/number of farms/animal units within buffer	13	Baliatsas et al. (2017); Baliatsas et al. (2019); Borlée et al. (2018); Borlée et al. (2015); Borlée et al. (2017); Fisher et al. (2020); Kiss et al. (2023); Loftus et al., 2015; Mendrinos et al. (2022); Quist et al. (2022); Schulze et al., 2011; Van Dijk et al. (2016b); Van Dijk et al. (2017)
Other[c]	8	Borkenhagen et al. (2020); Hanif and Martini, 2019; Hatcher et al. (2017); Hill et al., 2005; Hill et al., 2006; Loftus et al., 2020; Merchant et al., 2005; Müller-Rompa et al., 2018

Note: Some studies contributed more than one result and are represented in multiple rows.
Abbreviations: AFO (animal feeding operation), CAFO (concentrated animal feeding operation), DEQ (Department of Environmental Quality), GIS (geographic information system), $PM_{2.5}$ (particulate matter with aerodynamic diameter ≤ 2.5 mm).
[a] Water quality: Presence and concentration of antibiotic residues, bacteria, nitrate concentration in groundwater, wastewater sample.
[b] Other (e.g., outbreak of illness among animals, amount of animal waste, density of flies in the household, industrial hog operations (IHO) employment; Farm residence, parent's farm work, raising swine and/or other livestock, adding antibiotics to feed; environmental characteristics derived from satellite data or terrestrial monitoring; private well prevalence).
[c] Other (e.g., outbreak of illness among animals, bioaerosol sample collection, estimated daily AFO plume exposure based on distance to AFOs, AFO size, and daily wind speed and direction, employment at IHO, amount of animal waste).

Among these studies, most examined exposure disparity and a limited number of studies investigated disparities in relation to health associations. Very few studies evaluated both disparities in exposure and health associations. While in recent years, more studies have examined environmental justice and vulnerability in relation to AFOs/CAFOs exposure, results have varied by location with some studies reporting that AFOs/CAFOs may be disproportionately located in disadvantaged, marginalized communities such as those with a high percentage of racial/ethnic minority or low SES persons (Lenhardt and Ogneva-Himmelberger, 2013; Son et al., 2021a). On the other hand, other studies reported no association or mixed findings (Carrel et al., 2016; Galarraga et al., 2022). Although findings were not consistent across studies, findings of this systematic review suggest that some subpopulations have higher disparities in exposure and/or higher health response from AFO/CAFO exposure. Findings of the studies we reviewed suggest that racial/ethnic minority populations (e.g., NHB, Hispanic), people with low SES, and people living in poverty may have higher exposure to AFOs/CAFOs (Galarraga et al., 2022; Hall et al., 2021; Holcomb et al., 2022; Kravchenko et al., 2018; Lenhardt and Ogneva-Himmelberger, 2013; Mirabelli et al., 2006a; Ogneva--Himmelberger et al., 2015; Son et al., 2021a, 2021b; Wilson et al., 2002; Wing et al., 2000), although some studies found the opposite or no association for people of color, poverty, or education level (Carrel et al., 2016; Fisher et al., 2020; Galarraga et al., 2022; Khanjar et al., 2022). Also, this review suggests that urbanicity/rurality and age (e.g., younger or older populations) are relevant for vulnerability for higher disparities in exposure to AFOs/CAFOs, although findings varied across studies (Douglas et al., 2021; Holcomb et al., 2022; Ogneva-Himmelberger et al., 2015; Son et al., 2021b). In the assessment of health disparity regarding AFOs/CAFOs exposure, this review observed that racial/ethnic minority persons, people with low SES, younger or older people, and women may have higher health response from AFOs/CAFOs exposure (Ayala-Ramirez et al., 2023; Holcomb et al., 2022; Kravchenko et al., 2020; Quist et al., 2022).

Findings were inconsistent across studies, populations, which metrics were used for AFO/CAFO exposure assessment and variables related to environmental justice and vulnerability. A wide variety of variables were used to incorporate several aspects of disparities. The most commonly investigated variables for disparities were race/ethnicity and SES (Ayala-Ramirez et al., 2023; Carrel et al., 2016; Douglas et al., 2021; Fisher et al., 2020; Galarraga et al., 2022; Hall et al., 2021; Holcomb et al., 2022; Khanjar et al., 2022; Kravchenko et al., 2018, 2020; Lenhardt and Ogneva-Himmelberger, 2013; Mirabelli et al., 2006a;

Table 3
Summary findings of environmental justice and vulnerable populations.

	EJ and vulnerability in relation to exposure				EJ and vulnerability in relation to health association			
	Number of studies [Reference]	Findings for vulnerable population			Number of studies [Reference]	Findings		
		Higher exposure	Lower exposure	No association		Higher association	Lower association	No association
Race/ ethnicity	13 [Carrel et al., 2016; Galarraga et al., 2022; Hall et al., 2021; Khanjar et al., 2022; Lenhardt and Ogneva-Himmelberger, 2013; Mirabelli et al., 2006a; Ogneva-Himmelberger et al., 2015; Son et al., 2021a; Wilson et al., 2002; Wing et al., 2000; Holcomb et al., 2022; Kravchenko et al., 2018; Son et al., 2021b]	Hispanic [Galarraga et al., 2022; Lenhardt and Ogneva-Himmelberger, 2013; Son et al., 2021a], people of color [Hall et al., 2021], Black/African American [Lenhardt and Ogneva-Himmelberger, 2013; Wilson et al., 2002; Holcomb et al., 2022; Kravchenko et al., 2018], NHB [Son et al., 2021a; Son et al., 2021b], higher RI for NHB [Son et al., 2021a], American Indian [Kravchenko et al., 2018], non-White [Mirabelli et al., 2006a; Wing et al., 2000], minority population [Ogneva-Himmelberger et al., 2015]	people of color [Galarraga et al., 2022]	non-White [Carrel et al., 2016], people of color [Khanjar et al., 2022]	5 [Ayala-Ramirez et al., 2023; Holcomb et al., 2022; Kravchenko et al., 2020; Quist et al., 2022; Son et al., 2021b]	Black/African American [Ayala-Ramirez et al., 2023], Asian [Holcomb et al., 2022], both White and African American females [Kravchenko et al., 2020], NHW [Son et al., 2021b], rural American Indian [Quist et al., 2022], rural Black [Quist et al., 2022], rural Asian [Quist et al., 2022]		
Low SES	14 [Carrel et al., 2016; Douglas et al., 2021; Galarraga et al., 2022; Hall et al., 2021; Khanjar et al., 2022; Lenhardt and Ogneva-Himmelberger, 2013; Mirabelli et al., 2006a; Son et al., 2021a; Wilson et al., 2002; Wing et al., 2000; Fisher et al., 2020; Holcomb et al., 2022; Kravchenko et al., 2018; Son et al., 2021b]	more deprived [Douglas et al., 2021], low median household income [Galarraga et al., 2022; Hall et al., 2021; Lenhardt and Ogneva-Himmelberger, 2013; Son et al., 2021a; Holcomb et al., 2022; Kravchenko et al., 2018; Son et al., 2021b], high % of people in poverty [Galarraga et al., 2022; Khanjar et al., 2022; Son et al., 2021a; Wilson et al., 2002; Wing et al., 2000], high enrollment of school lunch program as a proxy for low SES [Mirabelli et al., 2006a], low education [Son et al., 2021a; Kravchenko et al., 2018; Son et al., 2021b], higher EI for population without a college degree [Son et al., 2021a], publicly insured and uninsured [Holcomb et al., 2022], high % of uninsured [Kravchenko et al., 2018], low number of primary care providers [Kravchenko et al., 2018]		% with less than a college education [Carrel et al., 2016;], % of residents living in poverty [Carrel et al., 2016], education [Fisher et al., 2020]	4 [Ayala-Ramirez et al., 2023; Holcomb et al., 2022; Quist et al., 2022; Son et al., 2021b]	low household income [Ayala-Ramirez et al., 2023], highest median income category [Quist et al., 2022], private insurance [Holcomb et al., 2022], rural self-pay/uninsured [Quist et al., 2022]	low education [Son et al., 2021b], low median household income [Son et al., 2021b]	
Immigrant, foreign born status	2 [Galarraga et al., 2022; Khanjar et al., 2022]		foreign-born [Galarraga et al., 2022]	foreign-born [Khanjar et al., 2022]				
Urban/rural, population density	4 [Carrel et al., 2016; Douglas et al., 2021; Holcomb et al., 2022; Son et al., 2021b]	urban [Douglas et al., 2021], rural [Holcomb et al., 2022; Son et al., 2021b]		population density [Carrel et al., 2016]	3 [Holcomb et al., 2022; Quist et al., 2022; Son et al., 2021b]	rural [Quist et al., 2022], urban [Son et al., 2021b]		suburban/small town/rural [Holcomb et al., 2022]
Age (e.g., younger or older)	3 [Douglas et al., 2021; Ogneva-Himmelberger et al., 2015; Son et al., 2021b]	older [Douglas et al., 2021], younger [Ogneva-Himmelberger et al., 2015], older [Ogneva-Himmelberger et al.,			5 [Ayala-Ramirez et al., 2023; Hatcher et al., 2017; Holcomb	age <65y [Ayala-Ramirez et al., 2023], children [Hatcher et al., 2017], age ≥45y [Hooiveld		0-4/5–17/18-34/ 35–64/65+ [

(*continued on next page*)

Table 3 (*continued*)

	EJ and vulnerability in relation to exposure				EJ and vulnerability in relation to health association			
	Number of studies [Reference]	Findings for vulnerable population			Number of studies [Reference]	Findings		
		Higher exposure	Lower exposure	No association		Higher association	Lower association	No association
		2015], adults 18-59y [Son et al., 2021b], 60-74y [Son et al., 2021b]			et al., 2022; Hooiveld et al., 2016; Son et al., 2021b]	et al., 2016], age ≥65y [Hooiveld et al., 2016], age ≤17y [Son et al., 2021b]		Holcomb et al., 2022]
Sex					5 [Ayala-Ramirez et al., 2023; Holcomb et al., 2022; Kravchenko et al., 2020; Michalopoulos et al., 2016; Son et al., 2021b]	female [Ayala-Ramirez et al., 2023; 71], White female [Kravchenko et al., 2020], male [Michalopoulos et al., 2016]		male/female [Holcomb et al., 2022]
Health behavior	1 [Fisher et al., 2020]			smoking status [Fisher et al., 2020], alcohol use [Fisher et al., 2020]	1 [Ayala-Ramirez et al., 2023]	smoker [Ayala-Ramirez et al., 2023]		
Others					2 [Holcomb et al., 2022; Quist et al., 2022]			calendar year [Holcomb et al., 2022], well water usage [Quist et al., 2022], precipitation [Quist et al., 2022]

Note: We focused on findings identified by authors regardless of statistical significance; Study Holcomb et al., 2022; Son et al. (2021b) are represented in both panels as these studies investigated disparities in both exposure and health associations.
Abbreviations: EI (educational isolation), EJ (environmental justice), NHB (non-Hispanic Black), NHW (non-Hispanic White), RI (racial isolation).

Ogneva-Himmelberger et al., 2015; Quist et al., 2022; Son et al., 2021a, 2021b; Wilson et al., 2002; Wing et al., 2000). Others considered urbanicity/rurality, age, foreign born status, sex, smoking/alcohol use, and well water usage (Ayala-Ramirez et al., 2023; Carrel et al., 2016; Douglas et al., 2021; Fisher et al., 2020; Galarraga et al., 2022; Hatcher et al., 2017; Holcomb et al., 2022; Hooiveld et al., 2016; Khanjar et al., 2022; Ogneva-Himmelberger et al., 2015; Quist et al., 2022; Son et al., 2021b). Several factors such as different population characteristics, exposure patterns, intersectionality, neighborhood characteristics, and their interactions may affect disparities in AFO/CAFO exposure and health response. Given the complex disparity patterns related to AFOs/CAFOs exposure, more disparity studies for different populations and locations and using a wide range of indicators reflecting features of disadvantaged communities and individuals are needed.

This review found that studies considered various measures and exposure metrics to assess AFO/CAFO exposure. The most used measure for AFO/CAFO exposure was presence of or proximity to a facility or specific farm animals within some boundaries (e.g., ZIP code) or specified distance (i.e., buffers) (Ayala-Ramirez et al., 2023; Baliatsas et al., 2017; Baliatsas et al., 2019; Borkenhagen et al., 2020; Borlée et al., 2015; Borlée et al., 2017; Borlée et al., 2018; Carrel et al., 2014; de Rooij et al., 2019; Douglas et al., 2021; Fisher et al., 2020; Galarraga et al., 2022; Goldstein et al., 2016; Hall et al., 2021; Khanjar et al., 2022; Kiss et al., 2023; Mendrinos et al., 2022; Mirabelli et al., 2006a; Mirabelli et al., 2006b; Murray et al., 2020; Murray et al., 2021; Pavilonis et al., 2013; Poulsen et al., 2018; Quist et al., 2022; Rasmussen et al., 2017; Schultz et al., 2019; Shaw et al., 2016; Sigurdarson et al., 2006; Smit et al., 2012; Smit et al., 2014; Son et al., 2021b; van Dijk et al., 2016a; van Dijk et al., 2016b; van Dijk et al., 2017; van Kersen et al., 2022). Other studies applied several measures such as density of facilities, air pollution levels, amount of animal waste, odor severity, and water quality to estimate the exposure to AFOs/CAFOs. Given the multiple pathways through which AFOs/CAFOs could affect health, such as through air pollution, water quality, odor, and noise, the use of a single exposure metric does not fully reflect actual exposure to AFOs/CAFOs. Thus, more refined exposure assessment considering AFO/CAFO size, AFO/CAFO characteristics such as animal type, operation history, and manure management are needed including methods to reflect complex, multi-faceted AFO/CAFO exposure through multiple pathways.

The published studies demonstrated a trend of increased interest in AFO/CAFO exposure in recent years. The number of published studies on this topic in 2016–2020 increased by 230% compared to those published in 2006–2010. Although studies on the impacts of AFOs/CAFOs exposure have grown, research on the disproportionate health burden from AFOs/CAFOs exposure is still relatively limited, although the existing studies suggest important disparities.

In the review of study location, the most represented country was the United States (about 61%), followed by the Netherlands (about 24%). Among the studies conducted in the US, the most investigated state was North Carolina (about 33%), followed by Iowa (about 17%). Findings may vary across different study areas due to different population characteristics, social and physical environment, distribution and/or composition of characteristics and their interactions (e.g., racial/ethnic composition in urban/rural areas), as well as differences in AFOs/CAFOs. More studies in different areas are needed to evaluate the complexities reflecting different AFOs/CAFOs characteristics and diverse forms of environments across areas and communities. Such findings can contribute to the scientific evidence on vulnerabilities and potential differences and similarities in results across populations and conditions. Such research can inform decision-makers and communities to better craft environmental policy to protect public health and minimize health disparities.

While intensive livestock farming has benefits of efficiency for meat production, the growth of these facilities has caused significant negative impacts on the environment such as harmful airborne emissions (e.g., PM, sulfur dioxide, volatile organic compounds (VOCs), noise, odors), and poor water and soil quality (e.g., ground water pollution, adverse impacts on aquatic ecosystems). These complex mixtures of harmful emissions can adversely impact human health (e.g., respiratory disease, cancer) through several mechanisms (e.g., lung inflammation due to interactive effect between PM/endotoxin/ammonia, hazardous gases as sensory, respiratory irritants and infectious agents) for farm workers and nearby communities (Cole et al., 2000; Gržinić et al., 2023; Heaney et al., 2015). In this review, we found that various health outcomes/symptoms were investigated in relation to exposure to AFOs/CAFOs. Evidence reported that respiratory outcomes and symptoms were the most considered health outcomes, and findings suggested higher risk of these outcomes with higher AFO/CAFO exposure. A recent study conducted in the Netherlands reported that higher exposure to livestock farming is associated with a lower forced expiratory volume in 1 s (FEV_1) in adolescents (Kiss et al., 2023). Another study suggested that living in an area with a high livestock density may be a risk factor for exacerbations in chronic obstructive pulmonary disease (COPD) patients (van Dijk et al., 2016a). However, some studies did not observe evidence for an association between health and livestock exposure (Baliatsas et al., 2017).

In the review of data sources used by the identified studies, we observed that most studies obtained data from government or state databases to estimate exposure to AFOs/CAFOs (e.g., permit databases). The structure of these databases differs by state and may not have information on smaller facilities with fewer animals, which are not regulated. The quality of the underlying data used in each study may differ. Consistent, systematic, and comparable database system and management across locations are needed for future studies of environmental disparities of AFO/CAFO exposure and associated health impacts, especially to facilitate research across different areas.

This review has several limitations. We were unable to estimate overall associations between exposure to AFOs/CAFOs and health outcomes by quantitatively combining estimates from studies through meta-analysis as there was a relatively small number of studies with the same category of health outcomes and AFO/CAFO exposure assessment. Instead, we provided detailed information for each study and synthesized evidence by summarizing findings by study characteristics based on several criteria. Although meta-analysis is commonly used to combine results from multiple studies and provide an overall effect for a systematic review, it may lead to biased results when the studies are not sufficiently similar or are heterogeneous. We were unable to perform meta-analysis due to the number of identified studies and differences across studies. While systematic review may have limitations such as bias resulting from specific inclusion/exclusion criteria or selective reporting, a well-designed and properly conducted systematic review can provide a comprehensive overview and summary of current evidence, informing knowledge gap and research needs, which is valuable for researchers and policy makers (Boon et al., 2022; CRD, 2009; Cumpston et al., 2022; Knight, 2021; Mulrow, 1994; Quan and Liamputtong, 2023; Sriganesh et al., 2016). Publication bias may exist as studies that found unanticipated findings (e.g., negative or null results) may be less likely to be submitted.

To the best of our knowledge, this is the first systematic review of investigations of environmental justice and vulnerable populations related to AFOs/CAFOs exposure and/or associated health outcomes. This review suggests that exposure to AFOs/CAFOs may have adverse impacts on various health outcomes in communities living near AFOs/CAFOs, although some findings vary, such as by exposure assessment. We observed suggestive evidence that disparities exist with some subpopulations having higher exposure and/or health response in relation to AFO/CAFO exposure, although results varied across studies. The findings from this review provide valuable knowledge on AFOs/CAFOs exposure assessment, health outcomes and symptoms associated with AFO/CAFO exposure, and environmental justice and vulnerability, and highlight needed areas of future research.

CRediT authorship contribution statement

Ji-Young Son: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seulkee Heo:** Writing – review & editing, Methodology, Investigation. **Garam Byun:** Writing – review & editing, Methodology, Investigation. **Damien Foo:** Writing – review & editing, Methodology, Investigation. **Yimeng Song:** Writing – review & editing, Methodology, Investigation. **Brandon M. Lewis:** Writing – review & editing, Methodology, Investigation. **Rory Stewart:** Writing – review & editing, Methodology, Investigation. **Hayon Michelle Choi:** Writing – review & editing, Methodology, Investigation. **Michelle L. Bell:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119550.

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