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Teaching and learning about respiratory infectious diseases: A scoping review of interventions in K-12 education

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Abstract

The pandemic outbreak of COVID-19 has highlighted an urgent need for infectious disease education for K-12 students. To gather a better understanding of what educational interventions have been conducted and to what effect, we performed a scoping review. We identified and examined 23 empirical researcher- and teacher-designed studies conducted in the last 20 years that have reported on efforts to help K-12 students learn about infectious diseases, with a focus on respiratory transmission. Our review shows studies of educational interventions on this topic are rare, especially with regard to the more population-scale (vs. cellular level) concepts of epidemiology. Furthermore, efforts to educate youth about infectious disease primarily focused on secondary school students, with an emphasis on interactive learning environments to model or simulate both cellular-level and population-level attributes of infectious disease. Studies were only mildly successful in raising science interest, with somewhat stronger findings on helping students engage in scientific inquiry on the biology of infectious diseases and/or community spread. Most importantly, efforts left out critical dimensions of transmission dynamics key to understanding implications for public health. Based on our review, we articulate implications for further research and development in this important domain.

KEYWORDS

epidemiology, games, infectious disease, learning sciences, modeling tools, science education, simulations

1 | INTRODUCTION

Recent infectious disease outbreaks—such as the Avian Flu, SARS, H1N1 Flu, and most importantly COVID-19—indicate the growing threat that epidemics, especially respiratory versions, pose in today's society. The current COVID-19 pandemic has also revealed many continued challenges ranging from compliance with public health measures and vaccination hesitancy in containing or eradicating infectious disease outbreaks. While most of the current discussions have focused on COVID-19's impact on K-12 school closures and related learning losses (Bailey et al., 2021; National Research Council, 2021), little attention has been given to teaching and learning about infectious diseases themselves. Yet the loss of millions of lives, the impact on global, national and local economies, and threat of future pandemics put the need for learning and teaching about epidemics front and center on the K-12 science education agenda. This need has become so urgent that a call for a "microbiological literacy" (Timmis et al., 2019) has been recently issued, requesting that "all stakeholders possess a basic understanding of how society and its actions are intimately connected with our microbial world" (p. 11).

A critical issue in realizing this vision of microbiological literacy is supporting students' understanding of infectious disease at different levels. Yet infectious diseases as a topic are not explicitly addressed in current NGSS guidelines (NGSS Lead States, 2013). While some related topics at a cellular level (e.g., viruses) or perhaps even modeling tools (though none specifically related to infectious disease) might be incorporated as part of current standards, the aspects of infectious disease related to issues of public health—infectious disease epidemiology (Straif-Bourgeois et al., 2014)—are not addressed by standards as noted by Jacque et al. (2016):

> very few high schools teach biology in the context of 21st-century issues in health and disease, in large part because teachers lack cutting-edge, life-relevant health science curricula as well as access to the support needed to bring it into their classrooms, and then to teach it from an HL [health literacy] perspective (p. 45).

As a result, teaching about infectious diseases is not part of current pre-service or in-service teacher education, leaving teachers and designers on their own in developing activities, connecting them to standards, and fitting them into class curricula. Still, a number of teachers and designers have risen to this challenge, including a surprising number of designed, interactive learning environments, such as in-person simulations, analog and digital games, digital simulations, and modeling tools. Understanding and building on this work will be key to moving forward in K-12 epidemiological education.

In this paper, we seek to understand the different types of classroom interventions with infectious disease education and their outcomes developed and implemented by researchers and teachers with K-12 students. To accomplish this, we conducted a scoping review (Arksey & O'Malley, 2005) to identify interventions implemented in the last 20 years, with a focus on respiratory diseases. Our scoping review was guided by the following broader research question: *How are respiratory infectious diseases taught and learned in K-12 education*? We answer this question by identifying content, STEM interest, and other learning topics addressed in each study, by describing instructional interventions, research approaches, and by reviewing the participant demographics included in the research studies. In the next section, we outline a theoretical framework that helped focus our examination of K-12 infectious disease education, then describe the methods employed in the scoping review for searching and selecting pertinent articles for inclusion in the review. In the findings, we present our answers to the research questions and conclude with recommendations for future research.

2 | BACKGROUND

2.1 | Framing infectious disease epidemiology for K-12 students

To better understand how K-12 interventions promote learning about infectious diseases, we draw upon a framework of "infectious disease epidemiology" developed by Straif-Bourgeois et al. (2014). Their framework identifies three interconnected dimensions of infectious disease epidemiology: (1) basic biology of infectious disease, (2) epidemiology of disease, and (3) infectious disease epidemiology. The first dimension, the basic biology of the infectious disease, covers germs, viruses, and activity on the level of immune systems—anything that pertains to what happens inside the single human body or between two human bodies (i.e., transmission from one human to another human). Most research in K-12 education on students' conceptual understanding of infectious disease has been in this category. In addition, most of this work has focused on younger children, noting at what ages children tend to understand the idea of contagion (i.e., how a disease is passed from one person to another) and immune system response to the introduction of a germ (e.g., Au et al., 1999; Kalish, 1999; Parmelee, 1992; Siegal, 1988; Siegal & Peterson, 1998; Sigelman et al., 1996; Solomon & Cassimatis, 1999; Toyama, 2015). Recent research has examined high school students' understanding of a virus (Simon et al., 2017). Most research here has focused on HIV/AIDS (e.g., Gelman & Legare, 2009) or the common cold (e.g., Badani & Schonfeld, 2002), but little on the flu or other severe infectious respiratory diseases (Sigelman & Glaser, 2019) that could inform the learning and teaching of COVID-19 related interventions.

The second dimension, the epidemiology of disease, focuses on the process and temporal dimensions of infection, including concepts such as incubation/latent period, infectious period, and symptomatic period of infectious diseases. Much less is known about students' understanding of this area; in fact, these conceptions are almost entirely neglected in research on children's learning about infectious disease. For instance, there is little concern in existing literature with the concept that individuals may be infectious (i.e., have a virus in their bodies that can spread to others) but not be symptomatic, even though this is a critical vector in diseases like HIV/AIDS, Ebola, and COVID-19. Some limited research has considered students' understanding of causal chains, a "connect the dots" perspective linking risky contact with people who have an infectious disease to internalization of a disease agent, invisible events inside the body, and ultimately observable symptoms (Sigelman & Glaser, 2019, p. 12). Gelman and Legare's (2009) work explicitly discusses students' understanding of prevention of infection and found that this was a more difficult concept to understand for them than the idea of treatment. They hypothesized that this was because prevention does not involve a change of state and thus is less cognitively compelling. Children also seem to know more about transmission routes than about the function of vaccines and developing immunity (Jones & Rua, 2008).

Finally, the third dimension, the infectious disease epidemiology, or the ecosystem-level of understanding, relates individual actions to community impact and addresses herd immunity, human behaviors, and massive adoption of preventive techniques like hand washing, quarantine, and universal mask wearing—all behaviors that break the chain of infection at population levels. Much less is known here with the exception of Gelman and Legare's (2009) work which examined elementary, middle, and high school students' understanding of prevention in AIDS. They found that these concepts were difficult for students of all ages, most likely because sexual transmission is not a concept accessible to these age groups. Although a number of educational efforts like simulations of disease spread have been developed to convey larger social aspects of epidemiology (described in the next section), these are mostly designs with little attention to researching students' understanding of infectious disease epidemiology and related behavior.

While this particular framework has been developed for medical education, K-12 science educators and researchers can use it to map student learning on to interrelated dimensions of knowledge that align with those used by epidemiologists. For example, NGSS standard MS-LS1-1 calls for middle school students to explore the structure and function of living things. In doing so, students grapple with the fact that while viruses are living things, they are not typical because they are not made up of cells, but rather share common features of cellular life. Straif-Bourgeois et al.′ (2014) first dimension thus provides a meaningful context for youth engaging in the science embedded in this standard. Furthermore, the second and third dimensions dive deeply into the associated cross cutting concepts around the scaling of the phenomena. Thus, rather than shifting away from the NGSS, this framework allows K-12 science educators and researchers to identify currently underrepresented content while engaging with the cross cutting concepts and practices associated with epidemiology.

The current research—limited because so few studies are concerned with concepts related to epidemiology of disease and infectious disease epidemiology—suggests that while K-12 students might develop a basic biological understanding of what happens with germs in their bodies that expands with age, they struggle to comprehend the interconnected nature of epidemiologic spread on an ecosystem level. Students are particularly challenged with understanding concepts related to periods of viral infection (e.g., incubation, infectious, and symptomatic periods) as well as system perspectives that reveal connections between actions of the individual and impacts on the community, especially preventive actions. Notwithstanding where learning about these concepts and systems will be situated in K-12 education, there is a clear need for instructional interventions to help students understand the many interconnected dimensions of infectious disease epidemiology. It is the focus of this scoping review to examine interventions to teach about infectious disease, with a focus on respiratory infections, developed and implemented during the last 20 years.

3 | METHODS

We chose to conduct a scoping review of K-12 interventions about infectious respiratory diseases because this topic area has not been well developed or researched enough for a systematic review (Munn et al., 2018). A scoping review describes the extent, range and nature of research in a topic area (Pham et al., 2014, p. 371). It is by design a more exploratory method that surveys the research literature and addresses broader research questions with studies using a variety of designs. Other established methods such as a meta-synthesis (Suri & Clarke, 2009) or meta-analysis (Slavin, 1984) would have required a more substantial body of available studies and mature field of research with agreed upon measures which was evidently not the case for the topic of infectious disease learning in K-12 education. This scoping review was conducted following the five stages outlined in Arksey and O'Malley's (2005) framework and the recommendations proposed by Levac et al. (2010). The authors who conducted this scoping review bring a background in biology (Xin), science teacher education (Tofel-Grehl), learning sciences (Fields), and computer science education (Kafai).

First, the review focused on a central question: "How are infectious respiratory diseases taught and learned in K-12 education?" With this research question as our focus, we paid special attention to the use of online games, simulations, and virtual worlds because of their relative prominence within the literature on teaching and learning about respiratory infectious disease. In particular, online simulations that track the spread of infection allow multiple runs of different disease vectors and engage significantly larger numbers of students not possible in a physical setting. With the increased availability of educational technologies such as these (Collins & Halverson, 2009), educators are able to engage different instructional approaches to infectious disease that contextualize the examination of various sources of information, simulate outbreaks, and engage historical or narrative role play. We group these into the broad term "interactive learning environments" because of the "increasingly blurring" technical and cultural boundaries between modeling, simulations, and digital games (p. 1, NRC, 2011). As we share in the findings, these interactive learning environments have been particularly prominent approaches in the limited work on engaging K-12 students in inquiring into infectious disease. Most relevant to our effort is an earlier consensus report from the national academies (NRC, 2011) which focused on learning science through computer games and simulations. Games were seen as having the potential to address long standing issues such as the lack of interest many students display for science, leveraging the motivating nature of games with growing challenges, immediate feedback and tailored instruction. Simulations, on the other hand, addressed difficulties in understanding complex phenomena through accessible dynamic models. In its final assessment the committee noted that there was promising evidence that engaging with simulations fostered conceptual understanding, but less evidence regarding motivating students' interest in science. The committee's report on computer games was inconclusive due to a lack of a coherent evidence base with only recently emerging findings at the time. Of note, while the report covered a wide range of science topics and issues, only one of the included studies focused on infectious disease (Neulight et al., 2007). Thus, the current pandemic outbreak provides a compelling reason to revisit the learning potential of computer games and simulations, but with a sole focus on infectious diseases.

Second, we searched for relevant studies in the following databases. The initial search for articles published after 2000 was conducted in databases of ACM Digital Library, ERIC, and Google Scholar, with queries tailored to the functions of each database. We searched for articles that mentioned "infectious disease or pandemic or epidemic" and "teaching or education" with additional qualifiers such as "K-12," "simulation," "game," "modeling," according to the scope of databases. We also searched in relevant peer-reviewed research journals such as *Journal of Research in Science Teaching*, *Science Education (JRST)*, *Journal of Science Education and Technology (JSET)*, in professional publications such as *Science Scope (SS)* and the *American Biology Teacher (ABT)*, and in peer-reviewed proceedings of conference such as *Conference on Human*

Factors in Interaction (CHI), CHI *Play*, *Digital Games Research Association* (DiGRA), *Foundations of Digital Games* (FDG), and *Interaction Design and Children* (IDC).

Third, we identified relevant studies in a multistep search and filtering process. The initial searches generated 3456 items in all databases, which were later screened by titles and abstracts to determine their relevance and whether they were duplicated in multiple databases. Although our search terms and queries ensured comprehensive capture of papers pertinent to our research questions, the search also netted a large number of irrelevant papers. For example, although we circumscribed our scope within K-12 education, there were still papers looking at higher education and professional education. Also, interventions based upon sexually transmitted, skin-based, or insect-driven diseases such as HIV, Ebola, and Zika did not satisfy our inclusion criterion of respiratory disease but still appeared in search results. Interestingly, the largest proportion of irrelevant papers concerned the impact of COVID-19 on K-12 school administration and school re-opening rather than education about infectious disease. We then decided to manually browse the titles and abstracts of *all* the search results to identify as many relevant papers as possible. The manual title and abstract screening and duplicate removal excluded the vast majority of 3456 total results and preliminarily identified 108 relevant papers, which advanced to the next phase.

We then read through the full text of these 108 papers to further determine their inclusion. We only included papers by researchers and teachers that described the design of an intervention with students. Literature reviews, meta-analyses, commentary articles, and book chapters were excluded by this criterion. Altogether, 48 out of 108 papers passed our full text screening phase.

We noticed there were cases where multiple papers or multiple research projects were developed upon the same interactive learning environment. In consideration of the purpose of our scoping review to focus on teaching interventions, we decided to include only the one paper of a set on a single environment that most comprehensively introduced this interactive learning environment. For example, we identified four papers involving the game-based learning environment Crystal Island in our search (Lester et al., 2013; Rowe et al., 2010; Rowe et al., 2011; Spires et al., 2011). Among these four papers, the paper from Rowe et al. (2011) was chosen as a representational study because it is the most pertinent journal article, while the other papers were listed in small print in Table 1. Twenty-five papers were not included in the final list due to this reason but are shown in small print next to the primary paper studied in this review except in the cases of NetLogo and Whyville because of the large numbers of papers on each.

For the remaining 23 papers that passed screening, we exported their reference lists and used tools such as connectedpapers.com to identify other papers connected to them. Additional journals that were not searched previously were also added to backward search. The backward search generated 644 results, which were screened again by their title, abstract, and full text and were combined with our primary search and screening results. After excluding duplicates and studies that did not meet our inclusion criteria, no new paper was added to our final list (see Figure 1).

These steps resulted in a final list of 23 papers (see Table 1, column 1). Seventeen papers reported empirical studies designed and performed by researchers published in journals such as the *Journal of Science Education and Technology*, *Journal of Research in Science Teaching, and Science Education*, while six papers described teacher-generated activities, published in professional journals such as The *American Biology Teacher* and *Science Scope*. We decided to include these studies in the review because they reported on interventions implemented by teachers in

TABLE 1 Overview of studies teaching about respiratory infectious diseases in K-12 education

Name	*N*	Learner	Duration	Context	Publication	Intervention (type | technology)	Teaching focus	Epidemiology dimension	Research type
Anderson et al. (2016)	n/a	ES G = n/a D = n/a SES = n/a	n/a (4 mini-cycles)	School (H)	Sci. Scope	An integrated curriculum involving multiple interventions, e.g., CDC Outbreak (Investigate, Others | digital GM)	CU	BIO	Observational
Baltezore & Newbrey (2007)	n/a	HS G = n/a D = n/a SES = n/a	1.7 h (2 consecutive sessions in 1 week)	School (IP)	Am. Biol. Teach.	Glo-Germ (Exp or mod | non-digital SM)	CU, SInq	IDE	Observational
Bartlow and Vickers (2020)	n/a	HS G = n/a D = n/a SES = n/a	1.5 h (1 session)	School (IP)	Am. Biol. Teach.	A curriculum about zoonotic disease (Investigate | Others)	CU; SIng, Collaboration	BIO; IDE	Observational
Colella (2000)	16	HS G = 44%F, 56%M D = n/a SES = n/a	5.2 h (5 sessions in 3 weeks)	School (IP)	J. Learn. Sci.	Thinking Tags (Exp or mod | Participatory SM)	CU; SInq	ED; IDE	Pre–Post
Corredor et al. (2014)	82	MS G = n/a D = n/a SES = n/a	4 h (4 sessions in 4 weeks)	School (H)	J. Sci. Educ. Technol.	Virulent (Exp or mod | digital GM)	CU; SInq; Dynamic mental model	BIO	Quasi experimental
Crosby et al. (2019)	115	ES (parents) G = n/a D = n/a SES = n/a	n/a	School (H)	Int. J. Early Years Educ.	Find the germ (Information | digital GM)	CU	BIO	Pre–Post
Dumais and Hasni (2009)	35	HS G = 100%F D = n/a SES = n/a	1.3 h (1 session)	School (IP)	CBE—Life Sci. Educ.	A curriculum about influenza biology (Exp or mod, Others | non-digital GM)	CU	BIO	Pre–Post
Hendricks et al. (2015)	24	HS G = 58%F, 42%M D = n/a SES = n/a	25 h (10 sessions in 1 week)	Summer camp (IP)	ASEE Annual. Conference	A summer camp about bioengineering and global health	CU; INT	BIO; IDE	Pre–Post

TABLE 1 (Continued)

<table>
<tr><th>Name</th><th>N</th><th>Learner</th><th>Duration</th><th>Context</th><th>Publication</th><th>Intervention (type | technology)</th><th>Teaching focus</th><th>Epidemiology dimension</th><th>Research type</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>(Others | non-digital GM)</td><td></td><td></td><td></td></tr>
<tr><td>Holder et al. (2019)</td><td>n/a</td><td>HS
G = n/a
D = n/a
SES = n/a</td><td>4.5 h (3 sessions)</td><td>School (IP)</td><td>Am. Biol. Teach.</td><td>Slime mold quarantine (Exp or mod | non-digital SM)</td><td>SInq; Engineering design</td><td>BIO</td><td>Observational</td></tr>
<tr><td>Hug and Catz (2003)
Hug et al. (2005)</td><td>1712</td><td>MS
G = n/a
D = 91%AA, 4%L, 4%C, 1%A
SES = n/a</td><td>n/a (8 weeks)</td><td>School (IP)</td><td>Urban Education</td><td>How Can Good Friends Make Me Sick? (Exp or mod, Information | participatory SM)</td><td>CU; EG</td><td>BIO; IDE</td><td>Pre–Post</td></tr>
<tr><td>Jacque et al. (2013; 2016)</td><td>273</td><td>HS
G = n/a
D = n/a
SES = n/a</td><td>30 h (5 units with 5–6 lessons in each unit)</td><td>School (IP)</td><td>Health Educ. Behav.</td><td>The Great Disease Project (Information, Investigate | Others)</td><td>CU; SE; SInq; Behavior change</td><td>BIO</td><td>Pre–Post</td></tr>
<tr><td>Ketelhut (2007); Nelson et al. (2007)
Dede et al. (2004)</td><td>96</td><td>MS
G = 48%F, 52%M
D = n/a
SES = 6%FRL</td><td>10 h (10 sessions in 3 weeks)</td><td>School (H)</td><td>J. Sci. Educ. Technol.</td><td>River City (Investigate | VW)</td><td>SE; SInq</td><td>BIO; IDE</td><td>Pre–Post</td></tr>
<tr><td>Miller et al. (2004)</td><td>710</td><td>MS
G = 49%F, 49%M, 2%unknown
D = 3%A, 8%AA, 60%C, 16%L,1% NA, 5%mixed, 8% unknown
S = n/a</td><td>2.5 h (3 sessions)</td><td>School (H)</td><td>Microbiol. Educ.</td><td>MedMyst (Investigate | digital GM)</td><td>CU; SInq</td><td>BIO; IDE</td><td>Pre–Post</td></tr>
<tr><td>Neulight et al. (2007); Feldon and Gilmore (2006); and other 11 papers[a]</td><td>46</td><td>MS
G = 50%F, 50%M
D = 13%A, 13% AA, 47%C, 27% L
SES = 67%TA</td><td>n/a (10 weeks)</td><td>School (H)</td><td>J. Sci. Educ. Technol.</td><td>QuestionHub (Exp or mod, Investigate | participatory SM, VW)</td><td>CU</td><td>ED; IDE</td><td>Pre–Post</td></tr>
</table>

(Continues)

TABLE 1 (Continued)

Name	*N*	Learner	Duration	Context	Publication	Intervention (type | technology)	Teaching focus	Epidemiology dimension	Research type
Nieves (2020)	n/a	HS G = n/a D = n/a SES = n/a	n/a	n/a (OL)	Am. Biol. Teach.	SimPandemic (Exp or mod | digital SM)	CU; MD	IDE	Observational
Papadopoulou et al. (2020)	40	HS G = n/a D = n/a SES = n/a	n/a	School (OL)	iHSES	A curriculum about plague of Athens (Exp or mod, Information, Investigate | MD)	CU; MD	IDE	Pre–Post
Rosenbaum et al. (2007)	21	HS G = 71%F, 29%M D = 46%AA, 23%A, 20%L, 11%C SES = 62%LI	2 h (1 session)	School (IP)	J. Sci. Educ. Technol.	Outbreak@The Institute (Exp or mod, Investigate | digital GM, participatory SM)	CU; Dynamic system	IDE	Pre–Post
Rowe et al. (2009, 2011); McQuiggan et al. (2008)	137	MS G = 44%F, 56%M% D = 3% AI/AN, 2%A, 32%AA, 13%L, 50%C SES = n/a	2 h (1 session)	School (H)	Int. J. Artif. Intell. Educ.	Crystal Island (Investigate | VW, digital GM)	CU; SInq; EG	BIO	Pre–Post
Sadler et al. (2015)	1888	HS G = n/a D = 10%–15% AA/L/mixed, <5%A/NA SES = n/a	15 h (10 sessions in 2 weeks)	School (IP)	Sci. Educ.	Mission Biotech, Viral Quest (Investigate | digital GM, VW, Others)	CU; INT	BIO	Quasi Experimental
Shen et al. (2020)	n/a	n/a G = n/a D = n/a SES = n/a	n/a	n/a (OL)	Am. Biol. Teach.	Find the Source of Infection (Exp or mod, Investigate | digital SM)	CU	IDE	Observational
Taylor et al. (2010)	50	HS G = n/a D = n/a SES = n/a	4 h (4 sessions in 4 weeks)	Summer camp (H)	Futureplay	Epidemic: Self-care for Crisis (Exp or mod | digital GM)	CU; EG	BIO; IDE	Pre–Post

TABLE 1 (Continued)

Name	*N*	Learner	Duration	Context	Publication	Intervention (type | technology)	Teaching focus	Epidemiology dimension	Research type
Tyrrell et al. (2018)	78	HS G = 67%F, 33%M D = 1%A, 9%AA, 81%C, 4%mixed, 5%unknown SES = n/a	n/a	School (H)	SITE Int. Conf.	Pandem-Sim (Investigate | digital GM)	CU; INT; SInq	BIO; IDE	Pre–Post
Wilensky and Abrahamson (2006); Klopfer and Yoon (2004) and other 5 papers[b]	27	MS G = n/a D = 25%A, 25% AA, 25%C, 25% L SES = 63%FRL	4.2 h (5 sessions in 1 week)	School (H)	Annual Meeting AERA	NetLogo (Exp or mod | participatory SM, MD)	MD; SInq, complexity	IDE	Pre–Post

Note: **Learner**: ES = elementary school, MS = middle school, HS = high school; **G** = **gender** (F = female, M = male); **D** = **demographics** (AA = African American, A = Asian, C = Caucasian, L = Latina/o, NA = Native American, e.g., American Indian/Alaska Native), **SES** = **socio-economic status** (FRL = free or reduced lunch; TA = tuition assistance; LI = low income).**Context**: IP = in person; OL = online; H = hybrid. **Publication:** Am. Biol. Teach. = *The American Biology Teacher*; Annu. Meet. AERA = Annual Meeting of the American Educational Research Association; ASEE Annu. Conf. Expo. = American Society for Engineering Education Annual Conference & Exposition; CBE—Life Sci. Educ. = *CBE—Life Science Education*; Futureplay = *Proceedings of the International Academic Conference on the Future of Game Design and Technology*; Health Educ. Behav. = *Health Education & Behavior*; Int. J. Artif. Intell. Educ. = *International Journal of Artificial Intelligence in Education*; Int. J. Early Years Educ. = *International Journal of Early Years Education*; iHSES = International Conference on Humanities, Social and Education Sciences; J. Learn. Sci. = *Journal of the Learning Sciences*; J. Sci. Educ. Technol. = *Journal of Science Education and Technology*; Microbiol. Educ. = *Microbiology Education*; Sci. Educ. = *Science Education*; SITE Int. Conf. = *Society for Information Technology & Teacher Education International Conference*; Sci. Scope = *Science Scope*; Urban Educ. = *Urban Education*. **Intervention type**: Exp or mod = interventions in which students experience, simulate, model, or modify diseases; Investigate = interventions in which students investigate diseases (i.e., cause, source, mode of infection); Information = interventions in which students read, study, and evaluate various sources of information (historical documents, graphs, articles) to understand diseases; Others (e.g., presentations, information delivery). **Intervention technology**: GM = digital or non-digital games; SM = simulations (digital, non-digital, and participatory); VW = virtual worlds; MD = modeling; Others (e.g., profession cards). **Teaching Focus**: CU = conceptual understanding; SInq = scientific inquiry; SE = self-efficacy; INT = science or science career interest; EG = engagement; MD = modeling skills; Others as listed. **Epidemiological Dimension:** BIO = basic biology of infectious disease; ED = epidemiology of disease; IDE = infectious disease epidemiology.

[a]Feldon and Gilmore (2006), Fields et al. (2017), Foley and La Torre (2004), Foley and Kobaissi (2006), Kafai (2008), Kafai and Fefferman (2010), Kafai and Wong (2008), Kafai et al. (2007, 2010, 2017), Neulight and Kafai (2005), Strawhacker et al. (2021), Sivaraj et al. (2020).

[b]Klopfer and Yoon (2004), Klopfer et al. (2005, 2009), Tisue and Wilensky (2004a, 2004b), Wilensky and Stroup (2000).

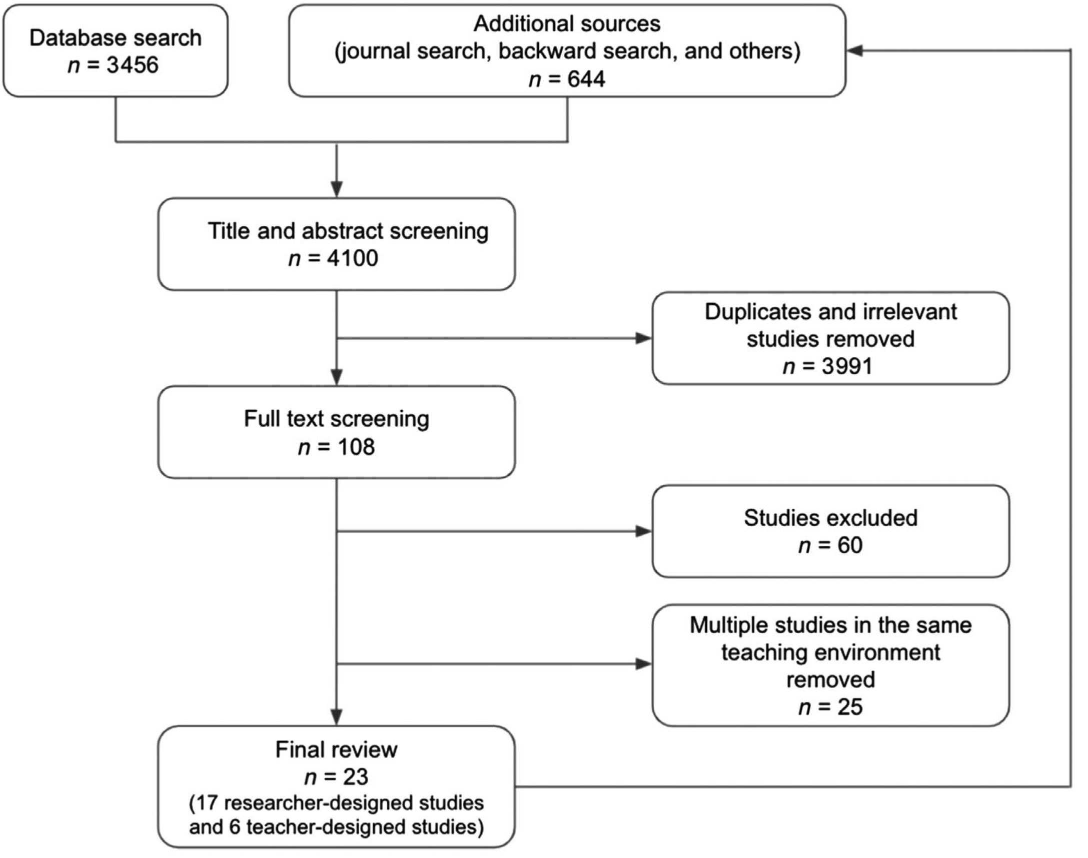

FIGURE 1 Flowchart of article selection process.

their classrooms and thus were deemed relevant and timely to developing the field's understanding of how infectious disease is taught in schools.

Fourth, in reviewing the final selection of papers, we took note of the number of students participating in research, reported gender, race using the following categories (African American, Asian, Caucasian; Latina/o; Native American), and socio-economic status (Figure 1). We also recorded whether the study took place in a school or afterschool setting and whether it was in person, online, or hybrid. After reviewing papers, we classified intervention types as experiential or modeling (where students experience, simulate, model, or modify diseases), investigation (where students specifically investigate some unknown aspect of a disease—real or fictional), informational (where students read, study, and evaluate information sources about a disease), and others (e.g., presentations, information delivery through various media). We noted any type of technologies used (digital or non-digital): games, modeling, simulations, participatory simulations, virtual worlds, and others (e.g., Sadler et al.'s (2015) profession cards). We coded learning outcomes as either conceptual understanding, scientific inquiry, self-efficacy, modeling skills, career interests, engagement, career interests, and other aspects. Finally, we created a special category for the content focus on infectious diseases using dimensions proposed by Straif-Bourgeois et al. (2014): basic biology of infectious disease, epidemiology of disease, and infectious disease epidemiology. Studies that addressed more than one dimension were double-coded. A minimum of two authors coded each of the papers, with discussion with a third author in case of disagreement. All codings have been compiled in one overview (see Table 1) and the general outcomes are reported in the next section—the fifth stage of the scoping review.

4 | FINDINGS

In this scoping review, we only identified a small number of efforts ($n = 23$) dedicated to helping K-12 students learn about infectious diseases, with a focus on respiratory diseases. In our review we included both researcher- and teacher-designed efforts to broaden the pool. Almost all of the reviewed studies (with the exception of Papadopoulou et al., 2020, and Strawhacker et al., 2021) were conceptualized and implemented before the COVID-19 outbreak. In general they represent efforts not part of standard science curricula. In the following sections, we answer each of our research questions by first reviewing intervention designs, trends in demographics, contexts and duration of each intervention before moving into specifics of learning outcomes, in particular what students were learning about infectious diseases.

4.1 | Topic #1: What kind of interventions for learning about infectious diseases have been designed?

We found a broad array of interventions designed by researchers and teachers to engage students in learning about infectious diseases. We classified these into a four types depending on the role students play in the learning process: (1) interventions in which students experience, simulate, model, or modify viruses or diseases ($n = 13$, 56%; e.g., Colella, 2000; Corredor et al., 2014); (2) interventions in which students investigate the cause, source, mode of infection ($n = 12$, 52%; e.g., Bartlow & Vickers, 2020; Ketelhut, 2007); (3) interventions in which students read, study, and evaluate various sources of information to understand diseases ($n = 4$, 17%), such as historical documents (Jacque et al., 2016; Papadopoulou et al., 2020) and selected research articles (Hug et al., 2005); and (4) interventions in which students are presented with content knowledge about infectious diseases through other means ($n = 3$, 13%), such as lectures, videos, lab activities, and field trips (e.g., Hendricks et al., 2015).

Of note, interventions included different types of digital and non-digital technologies. These types included (1) digital or non-digital games ($n = 11$, 48%) that provided adventure quests such as Mission Biotech Quest (Sadler et al., 2015) or MedMyst (Miller et al., 2004), (2) digital or non-digital simulations ($n = 9$, 39%) such as Pandem Sim (Tyrrell et al., 2018), (3) modeling tools ($n = 2$, 7%) such as NetLogo (Wilensky & Abrahamson, 2006), and (4) virtual worlds ($n = 4$, 17%) such as Crystal Island (Rowe et al., 2011) and RiverCity (Dede et al., 2004) that directed student inquiry into infectious disease outbreaks or Whyville which initiated virtual epidemic experiences for the player community (Kafai et al., 2010). We further note that many interventions ($n = 8$, 35%) allow students to play multiple roles with the support of one or more types of technologies. For instance, the "How good friends make you sick" curriculum combined information searching with experiencing and modifying the disease in the form of participatory simulations (Hug et al., 2005), while the virtual epidemic Whypox offered community infection updates as an additional information source for students to investigate using simulators embedded in the virtual world (Kafai et al., 2007).

While the large majority of these interventions utilized digital technology, there were also hybrid examples such as participatory simulations (Colella, 2000; Hug et al., 2005) in which students used digital tags to spread diseases in their classroom community or the Environmental Detectives augmented game in which students conducted augmented reality investigations on campus locations to track disease outbreaks (Rosenbaum et al., 2007). Others developed hands-on approaches such as books whose cover came with black thermochromic paint to make invisible germs visible, with a goal of changing young children's handwashing behavior (Crosby et al., 2019), employed ultra violet powder to make visible virus spread in context of classroom participatory simulation (Baltezore & Newbrey, 2007), designed slime molds to illustrate spread and promote engineering design (Holder et al., 2019), or used non-digital games, for instance to convey viral transmission.

4.2 | Topic #2: Who was targeted in interventions about infectious diseases?

Nearly all studies engaged middle and high school students, with only two interventions involving either kindergarten (Crosby et al., 2019) and elementary students (Anderson et al., 2016). While a total $N = 5350$ students were involved in all the studies reviewed, most studies were implemented with less than 100 participants, except for three projects (Hug & Catz, 2003; Miller et al., 2004; Sadler et al., 2015) with very large sample sizes that exceed or were close to 1000. We noted that reporting on gender, racial, and socio-economic status was lacking in many studies, as 11 studies (48%) did not report any demographic data. Those studies reporting gender demographics had about equal female and male students, most likely because they were situated in school settings. One study (Dumais & Hasni, 2009) was all female, while two studies (Rosenbaum et al., 2007; Tyrrell et al., 2018) involved a significantly larger proportion of female participants. Participants' ethnicity composition was reported in only 8 of the 23 studies. Only five of these studies were conducted in learning environments with more than 50% non-Caucasian students, with one study reporting 91% African American students (Hug & Catz, 2003). Socio-economic status was reported in only four studies; in three of these studies a majority of students received free or reduced lunch or tuition assistance.

4.3 | Topic #3: Where were students learning about infectious diseases?

The studies under review took place primarily in school settings, including a few that were online or hybrid, and this despite the lack of inclusion of infectious disease studies in national standards. Unlike other STEM topics that are often promoted in out-of-school settings, the majority of reviewed interventions ($n = 18$, 78%) took place in school settings with full or partial in-person instructions. Two studies (Hendricks et al., 2015; Taylor et al., 2010) were conducted in a summer camp, and three studies (Nieves, 2020; Papadopoulou et al., 2020; Shen et al., 2020) adopted a full online format since they were conducted after school lockdown caused by COVID-19. Ten studies were hybrid, including both in-person as well as computer- or web-based activities. No study addressed home and family settings as a place in which students could learn about infectious disease even though prior research identified parental caretakers as a critical source of information for children (Toyama, 2015). Often it was not clear in descriptions how many hours students participated in instructional activities; only 15 studies reported the number of hours involved. On average, the interventions in studies that mentioned durations lasted 7.5 h in total, varying between 80 min in one single session (e.g., Dumais & Hasni, 2009) to 6 weeks of daily classes (∼30 h; e.g., Jacque et al., 2016).

4.4 | Topic #4: How was research conducted?

The largest groups of studies were either comparative in nature using a pre–posttest design ($n = 15$, 65%) or observational ($n = 6$, 26%). Only two studies ($n = 2$, 9%) implemented quasi-experimental or comparative designs comparing different intervention formats across two groups of students. Sadler et al. (2015) compared a computer-game based versus a non-game approach using pre–post design with 1888 high school students nested within the classes of 36 biology teachers. Results indicated that students participating in both approaches demonstrated statistically significant gains in biological content knowledge but neither group demonstrated gains in science interest. Corredor et al. (2014) compared a game-based with a text-based condition in a 4-week-long intervention and found that high school students from the game-based condition were better in describing temporal-dependent interactions as measured by their drawings and interviews.

The largest bulk of studies adopted a range of methods, from interviews to classroom observations, as well as pre–posttests. For instance, Dumais and Hasni (2009) found that a class of 36 female high school students who initially exhibited a limited understanding of concepts related to viruses showed that their conceptions about influenza were more accurately related to the provided scientific knowledge after a 6-week intervention. Another example is Colella's (2000) participatory simulations in which students wore small computer devices that tracked their interactions. Participating high school students showcased a better understanding of the rules that underlie the complex system of an epidemic outbreak in their interactions as well as interviews.

All of the six teacher-designed interventions fell into the observational category. Most teachers attempted to do so with a focus on the inquiry process laid out in the NGSS (Anderson et al., 2016; Baltezore & Newbrey, 2007; Bartlow & Vickers, 2020; Holder et al., 2019). For example, Anderson et al.' "Outbreak" (Anderson et al., 2016) shares efforts to design an infectious disease unit for middle school students. Using mini-learning cycles, wherein the students collaboratively investigate growing levels of complexity around infectious disease, the authors seek to engage students in inquiry. Drawing on a series of free apps, the unit progresses from differences in cellular structure to the differences between bacteria and viruses, and culminates in a game simulation where students attempt to track disease spread across populations. In other articles found focusing on infectious disease instruction written for and by teachers, four of those articles shared teacher designed projects and lessons; the remaining two articles showcased resources that teachers might use to engage students in learning about infectious disease within their classrooms. Low and behold, researchers' and teachers' efforts to design for infectious disease understanding ultimately took a back seat to inquiry driven learning within the lesson plans and materials discussed.

4.5 | Topic #5: Which dimensions of infectious disease epidemiology were addressed in interventions?

In this section, we provide answers on the specific learning outcomes that address the three different dimensions of the framework of infectious disease epidemiology developed by Straif-

Bourgeois et al. (2014): basic biology, viral periods, and community spread. We observed that interventions targeted either basic biology or community spread of infectious diseases but only rarely addressed viral periods, and this mostly in an implicit manner. The following sections provide more detail on how exactly that was realized in the different interventions, with particular attention to which features of learning activities situated students' learning.

4.5.1 | Basic biology of infectious diseases

Of those studies addressing specific aspects of infectious diseases, over half of the studies ($n = 15$, 65%) focused on basic biology of infectious disease which covers germs, viruses, and activity on the level of immune systems—anything that pertains to what happens inside the single human body or between two human bodies focused on various aspects of viral or cellular level of transmission (i.e., individual-to-individual transmission; see "BIO" in Table 1). This finding is not surprising given that these topics are covered in the existing K-12 science curriculum. For instance, one of the few studies (Crosby et al., 2019) focused on young children (3–5 years old), aimed to help students understand the basic idea of germs as cells that could infect people. This study primarily used a book titled "A Germ's Journey" whose cover came with black thermochromic paint to make invisible germs visible, with a goal of changing children's handwashing behavior. Similarly, Dumais and Hasni (2009) included visual models of a virus in their 80-min mostly lecture-based intervention to introduce high school students to key aspects of a virus, its cell structure, mode of infection at the cellular level, and the nature of new strain emergence with influenza as an example. "The Great Diseases" is an example of a more elaborate curriculum that includes a 6-week infectious disease module (Jacque et al., 2016), which largely considers infection on a cellular level in concert with the immune system and interactions from vectors like insects, as well as some of the roles of vaccines, and many case studies of actual infectious diseases. The module as a whole focuses on health literacy problem-solving skills, and found positive results in a quasi-experimental study (273 students in experimental condition, 125 in control) with an emphasis on students' ability to evaluate health claims, interpret data, and generate accurate risk perceptions.

One approach to the viral and cellular aspects of infectious disease is through rich representations and inquiry models about virus features in dynamic representations or static visuals (e.g., Corredor et al., 2014; Sadler et al., 2015). For instance, Sadler et al. (2015) built a game-like 3D virtual environment in the Mission Biotech curriculum where students probe into DNA-level features of viruses through authentic biology research methods. In a virtual laboratory built in the environment, students manipulated virtual experiment instruments to extract viral DNA, conduct real-time polymerase chain reactions (PCR), and analyze the difference of the sample DNA sequences to distinguish various viruses. In a later stage of the curriculum, students were introduced to RNA viruses and their differences with DNA viruses including reverse transcription. The control intervention in this study used a narrative-based curriculum which also introduced students to nucleic acid level concepts and techniques. The study demonstrated that students in both narrative and gaming contexts improved their understanding of basic biological principles about DNA, genetic technologies, and pathogens and immune responses.

Another way that interventions approached the basic biology of disease was through narrative-centered investigations where students took on roles as investigators into historical or fictional epidemics. For instance, River City is a game-like multi-user virtual environment (MUVE) designed for supporting inquiry-based science curricula in middle school (Ketelhut, 2007). The 3D virtual world was set up in a 19th century city with unknown diseases transmitted among the population. Students took up virtual characters that were scientists to conduct a series of science experiment procedures such as talking to the citizens, collecting water samples, and observing microbes under microscopes in order to identify the pathogens of the diseases and the way they are transmitted. Similarly, in the virtual world of Crystal Island (Rowe et al., 2011), students investigated a mysterious disease spreading in a research camp, interacting with objects, talking to characters, and conducting virtual experiments to complete a series of missions to solve the mystery of the disease, namely the underlying microbe (virus or bacteria), the mode of infection (i.e., contaminated milk), and a treatment plan. The authors found that engagement with the digital narrative game/virtual world had stronger learning gains. Miller et al.' (2004) MedMyst web-based adventure game provided a similarly narrative-driven situation in which middle school students become members of a team focused on preventing the spread of an infectious disease in a distant future after a great plague outbreak. Students engaged in a series of missions, each being completed during a class period, focused on either the basics of microbiology (such as germ theory, infectious agents, disease vectors, immune system) or specific diseases like cholera and smallpox in which students conduct an epidemiology study and identify the source through interviews and maps and discuss implementation of a vaccination program. Of note, this particular design was strongly standards-focused, and though there was attention to prevention (i.e., vaccines) this emphasis was individual, not societal.

4.5.2 | Viral periods of infectious diseases

A much smaller number of interventions ($n = 2$, 9%) addressed the second dimension of infectious disease epidemiology which targets critical concepts such as incubation/latent, infectious, and symptomatic periods (see "ED" in Table 1). The few studies that addressed this dimension, did so by embedding incubation periods into the design of their infectious outbreak. For example, Colella (2000) introduced *Thinking Tags* to facilitate students' experimentation and inquiry into a technology-enabled, in-person simulation of disease spread. Thinking Tags are small wearable computers with infrared sensing devices that can communicate and display information about infection status. In this participatory simulation, the designers programmed rules for disease spread and encouraged the students of one classroom to figure out those rules. The designed virus was latent (invisible, as in asymptomatic) for 3 min, but any person whose tag had the virus would infect with 100% probability any person within the right proximity. In addition to incubation periods, the design also added for some participants immunity to the disease and inability to spread the disease. The evaluation of a classroom implementation illustrated that students figured out the rules that impacted the disease outbreak. Another example is the COVID-inspired SPIKEY-20 virus in the virtual world of (Strawhacker et al., 2021), a design that built on the much earlier Whypox virus (Kafai et al., 2010), but which contained new features such as explicit overlapping infectious and asymptomatic viral periods. This asymptomatic infectious period was apparent if players tested positive for the virus while not showing symptoms, and results showed that many players took advantage of the free, unlimited testing (which also had false positives and negatives that motivated multiple tests per day by many players).

4.5.3 | Community aspects of infectious disease

Finally, more than half of the interventions ($n = 15$, 65%) addressed the third dimension of infectious disease epidemiology, the community-level or systems-level concerns about infectious disease which covers elements of the societal spread and prevention of epidemics (see "IDE" in Table 1). In general, these studies tended to emphasize issues of probability and population-level spread, though only rarely did they include means of considering prevention at a population level (usually with vaccines, rarely with other preventive measures). Within these studies we identified three different approaches that use computational simulations but involve learners in different ways: (1) modeling tools, (2) participatory simulations, and (3) virtual epidemics.

One genre are computational simulations that provide students with modeling tools to design and observe epidemic outbreaks on a screen to better understand issues such as variability, randomness, and probability as they relate to population spread of a disease. Already an essential part of math and science education, modeling allows students to use mathematical knowledge they learn to solve real-world problems and engage in authentic science practices (NGSS and Common Core). For instance, Wilensky and Abrahamson (2006) focused on the modeling process as critical for students' understanding infectious disease as a complex system that included variability and randomness. They used agent-based modeling with NetLogo to allow students to play out individual agents as part of a larger simulation shown on a large screen. After students made hypothesized graphs of disease propagation, the class worked collectively by manipulating their agents within a set of rules to help the student achieve the graph. Of note, the students interacted through a central onscreen representation. This process effectively improved students' reasoning skills about complex systems toward more aggregate and non-linear models. A related example situates the use of these modeling tools in a historical context. Papadopoulou et al. (2020) used mathematical modeling with students to better understand the Athens' plague in 430 BC, interpreting historical texts in light of population density in different areas of Athens (e.g., Peloponnesian War refugees densely packed within the walls) with the SIR model (susceptible, infected, recovered) and the reproductive ratio (R_0) of the disease. They documented high school students' improved learning outcomes in mathematics and history.

A second genre are more direct participatory simulations which place learners as direct parts of a simulation themselves (i.e., person-to-person) in physical locations such as classrooms or campus settings to experience or investigate an actual epidemic outbreak. For instance, Colella (2000) used *Thinking Tags* to facilitate students' experimentation and inquiry into a technology-enabled, in-person simulation of disease spread. The students engaged in rich, iterative experimentation, coming up with more focused hypothesis-driven experiments over the course of several days. This is an example of a simulation design that promoted deep levels of inquiry. As already noted, embedded in the design were the overlapping latent and infectious periods of the virus. However, like many of the interventions focused on inquiry and experimentation, the intervention did not include any explicit connections to content about epidemiology or concerns about how to deal with an actual epidemic in real life. Another effort, *Outbreak @ The Institute*, combined participatory simulations with narrative roleplay inquiry in a "participatory reality" game that put students in dual roles as both public health inquirers as well as people who could (and did) get sick with a virtual virus (Rosenbaum et al., 2007). The authors noted that the game helped students to move from more abstracted goals like learning about bird flu to more person-level goals like preventing illness in themselves and their team. The game had multiple means of prevention (gloves, masks) and treatments (vaccines, medicines) as well as two types of tests (rapid and slow, the latter with better accuracy). Further, while there was a sophisticated model of infection in the game where infection was a discrete event with a probability (based on accumulated virus levels), students tended to treat the potential for infection as a continuous event (i.e., they thought removing themselves from the source of infection would keep them healthier). This research demonstrates some directions for future participatory simulations in more directly disrupting student misconceptions of viral infection and disease progression.

Finally, a third genre are virtual epidemics in which players join massive virtual worlds with millions of players and experience and investigate as participants an epidemic outbreak. Virtual epidemics integrate the experiential experience of participatory simulations and the community scale of computational simulations but also add a real-time factor. As the first designed virtual epidemic, Whypox represented a blend of measles and common cold making the virus symptoms visible by placing red dots on player's avatars and interrupting players' online chat by replacing words with sneezes (i.e., "achoo"). Research studies that investigated classroom integrations of Whypox (Kafai et al., 2007) demonstrated how upper elementary students were able to improve their understanding of the biology of disease while also changing their behaviors during the outbreak, becoming more systematic in running predictive simulators (Kafai et al., 2010), and writing and discussing the causes of the disease. Key findings from this virtual epidemic study with thousands of online participants revealed that the virtual epidemics not only promoted science talk (Kafai & Fields, 2013) and argumentation practices (Kafai & Wong, 2008) but also strongly affected players' actions in the virtual world (Kafai et al., 2007). In a community of millions, the Whypox infected thousands of players who responded with writing about their experiences in an online newspaper while also investigating (Kafai & Fefferman, 2010). A classroom implementation (Neulight et al., 2007) with upper elementary students illustrated how students could draw comparison between real and infectious diseases.

4.6 | Topic #6: What else did students learn?

Nearly half of all researcher- and teacher-designed studies ($n = 11$, 48%) focused on students' learning in terms of inquiry and problem solving skills, doing so in a variety of ways. For instance, in Ketelhut's (2007) study based on the River City MUVE, which involved 100 seventh-grade students, the research focused on students' data gathering behaviors as scientific inquiry practices in the MUVE and found a positive correlation with students' self-efficacy in scientific inquiry. Similarly, Colella's (2000) *Thinking Tags* examined how high school students experimented and engaged in different inquiry activities about infectious spread. As another example, Jacque et al.' (2013, 2016) evaluation of "The Great Diseases Project" indicated that students' posttests showcased better understanding of claim evaluation and risk assessment than a comparison group. A subset of findings from the Hug et al. (2005) study highlighted students' struggles to collect information from pre-selected text sources. Of note, in several of these studies, designers sometimes put a higher emphasis on inquiry and problem solving than on any specific dimensions of infectious disease epidemiology. We found this trend especially strong in the teacher-designed studies.

4.7 | Topic #7: Did interventions about infectious diseases promote interest in STEM?

While this was not the primary focus of our scoping review, we noted that some papers explicitly studied student interest in STEM and epidemiology ($n = 3$, 13%). The three studies investigated whether students' learning about infectious diseases also led to greater interest in science or STEM and/or pursuing careers. The only study showing promise was Hendricks et al.' (2015) global health summer camp which featured lectures and lab activities about bioengineering topics including infectious disease. Their study only found a near statistically significant difference in career interest in science or engineering in pre- and posttest of 24 high school students, although it needs to be considered that the students admitted to the summer camp were already selected because of their high interest in related fields. The two other studies did not report improved interest. Sadler et al. (2015) measured 1888 high school students' interest in science and careers after completing a biotechnology curriculum but did not find any significant changes in pre- and posttests. The one study (Tyrrell et al., 2018) specifically addressing epidemiology involved Pandem-Sim, a computer-based immersive learning experience, students acted as epidemiology experts and collaborated and analyzed medical reports. The participating 78 high school students were asked about their STEM career interest especially in epidemiology and biomedicine, but no statistically significant difference was found between pre- and posttests.

5 | DISCUSSION

The recent urgent call (Timmis et al., 2019) for a microbial literacy of all citizens including students, policymakers, business leaders—indeed, everyone—demanded that stakeholders develop a basic understanding of our microbiological world for their own personal decisions as well as for providing knowledgeable input for policy making at all levels of society. In the following sections we will discuss first what we learned from our scoping review about teaching and learning about respiratory infectious diseases, then address the limitations of our scoping review, and outline implications for K-12 science education research and practice.

5.1 | Taking stock of infectious disease learning and teaching in K-12 education

First, most studies focused on high and middle school students, failing to adequately explore impacts and outcomes for elementary and younger students. Second, few studies provided information about the demographics of the students reached, a topic all the more concerning in light of the inequities regarding race and income brought to attention during the recent COVID-19 pandemic. Third, nearly all studies focused on classrooms, neglecting highly relevant learning in informal, home, and online settings. Future studies need to broaden reach to include younger children, report on (and reach out to) diverse communities that bring different perspectives to infectious disease concerns, and connected areas of students' lives including but also beyond the classroom.

Our review also revealed some myopia regarding what aspects of infectious disease epidemiology were covered. The interventions tended to address only the basic biology or the community spread aspects of infectious disease, with rare (and then only implicit) attention to critical viral periods such as incubation phase or non-symptomatic expressions that are crucial to some of the most severe epidemics in history (including COVID-19). Nearly half of the teacher- and researcher-designed studies primarily sought to engage infectious disease education as a vehicle for teaching inquiry with a tendency to underemphasize content knowledge about infectious disease epidemiology. Because of this, quite often the content shared about infectious disease, especially at a societal level, is limited. This limitation is likely due to the lack of learning standards on infectious disease within the NGSS, a topic we consider further below.

Our analysis showed only limited success of reported interventions. Overall evidence about learning impact varied, even in those studies that sampled larger numbers of classrooms, though insights from qualitative work provide some information about concepts students may tend to struggle with, such as the role of probability in infection and testing as well as the concept of infection as a discrete (rather than continuous) event (e.g., Rosenbaum et al., 2007; Wilensky & Abrahamson, 2006). Finally, studies reported only marginal success in raising students' interest in STEM and epidemiology. However, studies such as Rosenbaum et al. (2007) and Ketelhut (2007) which allowed students to take active roles—for instance through narrative games or as active participants in simulations and models—did report that students' perspectives and/or self-efficacy about infectious disease changed.

5.2 | Limitations

Upfront, we want to note several limitations. One important one is that our scoping review was the first comprehensive effort to summarize what we know about learning and teaching of respiratory infectious disease in K-12 education. Because of its relevance for learning about COVID (also a respiratory disease), we focused on respiratory-driven diseases and excluded studies which had examined other infectious diseases such as HIV, Ebola, or Zika transmitted via other disease vectors such as blood, skin, insects, or feces. Additional scoping reviews would be valuable in these areas to develop a more comprehensive understanding of K-12 infectious disease education in general. Future studies could investigate these bodies of research on other types of transmission modes of infectious diseases and examine potential intersections with what we know about respiratory diseases—topics which have not been addressed in educational research so far. We also excluded the few interventions targeted at undergraduate students since these learners come with different backgrounds, motivations, and learning contexts. Again, infectious disease education in higher education should be the focus of a separate review on its own.

Further, our review does not include some of the research currently underway, motivated by the immediacy and urgency of the COVID-19 pandemic. We know that shortly after the start of COVID-19 in March 2020, several research efforts were initiated with support from government and private foundations, some of which resulted in early publications that have been included in our review (e.g., Greenberg et al., 2020; Papadopoulou et al., 2020; Strawhacker et al., 2021), but others which are still in progress or under review. Some of these studies may include elements of infectious disease epidemiology, inspired by the COVID-19 pandemic, that were more rare in earlier interventions. For instance, "The Great Diseases Project" researched earlier by Jacque et al. (2016) has a new online module explicitly about COVID-19, but without recently published research on that newly included content. The module includes a specific case study of spread in a meat-packing plant in the United States, a close look at amino acids and spike proteins in the SARS-CoV-2 virus, and public health strategies for containment, covering both cellular levels biology of infectious disease, progression of the disease (including long-term chronic cases) as well as population level trends and containment. However, to our knowledge, no research on the unit's use has yet been published.

Similarly, a new virtual epidemic, SPIKEY-20 (updated from the Whypox epidemic nearly two decades earlier), included viral periods (e.g., a period of non-symptomatic contagion) made explicit with the capacity for players to self-test for the presence of the virus, along with false positives and false negatives to emphasize real-life parallels of probabilities in testing. In addition, there were a variety of preventive measures players could use to slow the spread of disease (e.g., covering your mouth prior to coughing; wearing single-use or reusable masks) that also introduced economic aspects of epidemiology including a reduction in player salary while infected and differing costs (and effectiveness) of personal preventive equipment. Early publications about SPIKEY-20 demonstrate increases in players' use of virtual preventive measures and of frequent virus testing, with promises of more findings to come (Strawhacker et al., 2021). Both of these new interventions introduced aspects of viral periods and population-level forms of prevention rarely seen in earlier studies but with direct parallels to common activities in the COVID-19 pandemic. We thus expect more interventions and studies to be published in coming years, which may provide particularly relevant insights with research conducted during an actual pandemic outbreak rather than as an historical or hypothetical event. In the following sections, we discuss what we learned about the limitations of reviewed research and outline directions for learning and teaching about infectious diseases in K-12 education.

5.3 | Implications for K-12 science education research and practice

The COVID-19 pandemic illuminates the vital need for science standards and policy to specifically support teaching and learning about infectious disease epidemiology in K-12 education. Teaching about respiratory infectious diseases, as well as those that employ other transmission mechanisms, is no longer about diseases that ravage places far from home or happened in a distant past. Youth need an opportunity to engage with the science and practice of infectious disease epidemiology in classroom environments. Currently we experience a scourge of misinformation regarding science, scientific process, and engagement with scientific knowledge. The ill-informed notion that science must be absolute when the very nature of science is rooted in its tentativeness (Lederman et al., 1998) indicates a growing urgency for educators to engage in socio-scientific learning to help engage a more informed and educated populus. This is likely due to the lack of learning standards on infectious disease within the NGSS (cf. Miller et al., 2004).

Thus, learning and teaching about infectious diseases in science education should embrace the full spectrum of infectious disease epidemiology, but K-12 science teachers and researchers need to consider carefully what, when, and how it should be included in their classrooms. Our scoping review showed that most teachers and several researchers developing curricula (e.g., Jacque et al., 2016) either sought to engage infectious disease education solely as a vehicle for teaching *cellular*-level infection (including individual immune systems) and/or the process of *inquiry* without accompanying content knowledge of key concepts of epidemiology that involve societal-level infection and prevention trends. Right now teachers and designers try to engage the NGSS content standard A (science as inquiry) and content standards C (the interdependence of organisms) as anchors for their efforts. Because of this, quite often the content shared about infectious disease is limited. While the rationale offered within practitioner efforts is the value of epidemiologic education, their lessons and reports of those efforts indicate that the time and focus ultimately turned to the inquiry process. This effort reflects an excellent example of the potential of teacher- and researcher-led efforts and the limitations they face due to the lack of standards around infectious disease. Reflecting back on the infectious disease epidemiology framework's three dimensions, we can see how this effort works toward the first domain (basic biology) but ultimately fails to scaffold students in deeper understandings of the second and third domains. What the COVID-19 pandemic has laid bare is that teaching youth about infectious disease should not be a luxury or standards-based opportunity, but a societal necessity. Policies and standards need to match this societal necessity to support teachers and designers in implementing infectious disease epidemiology interventions in science.

Furthermore, we note that missing from current framings of understanding infectious diseases in K-12 education is a fourth, equally critical dimension of how it is situated within socio-political contexts. The COVID-19 pandemic has revealed stark inequities in how disease spread impacted communities, who had access to health care and treatment, and which information was collected and shared with the public (e.g., Bradford et al., 2021; O'Keefe & Walls, 2021). These disparities have only recently begun to be addressed by examining how community members made sense and critically examined the data and information shared with them (see Greenberg et al., 2020). We need to understand and teach infectious disease science in K-12 education not only as it relates to protection for an individual or even a small community, but as it relates to our social communal responsibilities in order to stem disease spread. This points to the need for a specifically socio-scientific understanding of infectious disease in all levels of education.

Finally, we see potential for making interdisciplinary connections beyond the scope of science education. For instance, modeling tools are often used in mathematics education. Yet connections to social sciences are also possible as the research by Papadopoulou et al. (2020) illustrated when high school students learned about Susceptible-Infected-Recovered (SIR) models in epidemiology in the context of the plague of Athens in 430 BC. Another example is a focus on data literacy (e.g., Greenberg et al., 2020; Jacque et al., 2016) which can stretch between several K-12 disciplines. Our review suggests that the interdisciplinary connections in infectious disease epidemiology have barely begun to be explored.

6 | CONCLUSIONS

Overall, our scoping review revealed a broad array of interventions aimed at supporting K-12 students' learning about infectious disease across two decades of work, using everything from books and lectures to slime mold to augmented reality and virtual worlds. However, the number of studies (researcher- and teacher-designed) covering the K-12 spectrum is too small to present a conclusive research base. We identified the limitations in what had been targeted in terms of students' learning of infectious disease epidemiology and outlined implications for where national standards, educational research and practice needs to focus on to move ahead. While engaging youth in learning about respiratory disease has historically been perceived as the study of something that happens far away, the predictions from scientists indicate that this will not be the last pandemic of our lifetimes. Thus, there is a significant need for robust teaching and learning around both the scientific understandings of epidemiologic disease spread and the socio-scientific issues around scientific knowledge related to vaccines and the process of developing and disseminating scientific knowledge.

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