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RESEARCH ARTICLE

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# Facility design and worker justice: COVID-19 transmission in meatpacking plants

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## Abstract

**Background:** Meatpacking plants were major sources of COVID-19 outbreaks, posing unprecedented risks to employees, family members, and local communities. The effect on food availability during outbreaks was immediate and staggering: within 2 months, the price of beef increased by almost 7% with documented evidence of significant meat shortages. Meatpacking plant designs, in general, optimize on production; this design approach constrains the ability to enhance worker respiratory protection without reducing output.

**Methods:** Using agent-based modeling, we simulate the spread of COVID-19 within a typical meatpacking plant design under varying levels of mitigation measures, including combinations of social distancing and masking interventions.

**Results:** Simulations show an average infection rate of close to 99% with no mitigation, 99% with the policies that US companies ultimately adopted, 81% infected with the combination of surgical masks and distancing policies, and 71% infected with N95 masks and distancing. Estimated infection rates were high, reflecting the duration and exertion of the processing activities and lack of fresh airflow in an enclosed space.

**Conclusion:** Our results are consistent with anecdotal findings in a recent congressional report, and are much higher than US industry has reported. Our results suggest current processing plant designs made rapid transmission of the virus during the pandemic's early days almost inevitable, and implemented worker protections during COVID-19 did not significantly affect the spread of the virus. We argue current federal policies and regulations are insufficient to ensure the health and safety of workers, creating a justice issue, and jeopardizing food availability in a future pandemic.

KEYWORDS

COVID-19, disease transmission, meatpacking plants, mitigation measures, policies and regulations

## 1 | INTRODUCTION

In April of 2020, meatpacking plants in the United States experienced a surge in the number of COVID-19 infections among their workers. By the end of April, some 23 states had reported at least one infection related to the meat industry. Of these 23 states, 17 reported infection rates ranging from 1% to 18% among worker in meatpacking facilities.[1] The number of meatpacking workers with COVID-19 rose to more than 20,000 by the end of May 2020. By November, despite constituting only 30 percent of all food and beverage manufacturing employees,[2] meatpacking plant workers account for over half of all COVID-19 cases within the US food sector.[3] In the pandemic's early stage, major food distributors such as Tyson Foods, JBS USA, Smithfield Foods, and Cargill were forced to temporarily close their facilities as workers tested positive for the virus.[4]

Five meatpacking conglomerates dominate the industry with nearly 80% of beef production in the United States. In 2017 alone, the industry as a whole processed nearly 42.2 billion pounds of chicken; 26.3 billion pounds of beef; 5.9 billion pounds of turkey; 150.2 million pounds lamb and mutton and 25.6 billion pounds of pork.[5] Before the pandemic, many plants were operating at very high utilization to capacity rates, upwards of 104%.[6] When plants began closing, the tension between changing demands and a significant dependence on a large labor market had far reaching effects.[7,8] Supermarkets began reporting meat shortages and the price of beef rosed by 6.6% between March and April 2020.[9] Counties that housed or were located within 15 miles of a meatpacking plant, reported almost twice the national average of COVID-19 infections.[10,11] The presence of a slaughterhouse within a county was associated with an additional four to six cases per 1000 residents and excess COVID-19 infections associated with livestock plants represented 6%–8% of all US cases.[12]

Major epidemics have historically had a disproportionate occupational morbidity and mortality effect on workers.[13] The workforce demographics of the meatpacking industry were no different: COVID-19 had a lopsided impact on low income and minority populations.[14] Roughly 35% of meatpacking-dependent counties reside in high-poverty counties, compared to 26% in other rural counties.[15] Plant workers, often considered essential workers, tend to be from low-income, large families, and multifamily communities with significant language barriers and precarious finances.[13] Low pay, long shift hours, job insecurity, and crowded housing accommodations are commonalities shared by workers in both the United States and Europe.[16] The proportion of immigrants in a typical US meatpacking plant, for example, South Dakota with 58%, and Nebraska with 66%, is also substantive, ranging between 40% and 66%.[17,18] The concentration of migrant workers in the meat-packing industry also serves to enhance structural inequities.[19] Workers are often unaware of regulations and health protocols due to the language barriers.[20]

The effects of COVID-19 on meat processing workers were cascading, but began at the plant. In this research we simulate the spread of the COVID-19 virus among workers using a general meatpacking plant layout. We estimate the effectiveness of personal protection measures suggested by government agencies in reducing COVID-19 transmission on the processing floor. We compare these results with the measures ultimately instituted by the companies themselves. Although environmental and health concerns have long been studied (e.g., see Clare et al.[21]), less attention has been paid to the health of occupational workers.[19] To the best of our knowledge, this study is the first to explore the efficacy of worker protections for COVID-19 in the meatpacking plant industry, and its cascading effects on community health and food availability. We begin with a review of the critical features of meatpacking floor facilities, outlining the potential transmission pathways. We then describe our general approach and outline our simulation model specifications. Finally, we discuss the results of our modeling within the context of current Occupational Safety and Health Administration (OSHA) policy, recommendations, and company mitigation measures.

## 2 | BACKGROUND

The rapid spread of COVID-19 among meatpacking plant workers and neighboring communities was not limited to the United States facilities in Gutersloh, Germany[22] and Anglesey, United Kingdom also experienced large scale outbreaks.[23] Plants in Brazil, and Australia closed due to high COVID-19 rates of infection.[24,25] Some 4000 JBS employees in Brazil were COVID-19 positive, with 6 deaths and 23 plants temporarily closed.[25] These global outbreaks suggest unique structural and operational design features that predispose processing plants for rapid transmission of droplets and aerosols (Table 1). Under normal conditions, a significant amount of work in these plants is performed in close quarters.[26–29] Similar to a well-publicized study of virus transmission in an air-conditioned restaurant in Guangzhou,[30] the Heating, Ventilation, and Air Conditioning (HVAC) design of processing plants predisposes increased transmission risk for workers.[31] Operations result in a dense production of aerosols[23] in an enclosed space that requires lower temperatures,[32–34] very high or very low relative humidity,[33] and metallic surfaces to mitigate bacterial spread.[23,35] In addition, workers share the same space for long periods, positioned face-to-face and shoulder-to-shoulder, and many share the same shuttle buses or carpool for their work commutes.[1] Workers also commonly use shared breakrooms, lunch facilities, and sometimes even housing.

There are three main methods of transmission for respiratory viruses—contact transmission, droplet transmission, and airborne transmission.[29,36] Contact transmission spreads through direct contact with an infected person or item (fomite transmission). Droplet transmission spreads via respiratory droplets containing the virus and airborne transmission occurs with exposure to small respiratory droplets and particles suspended in the air containing the virus. Airborne transmission exposure can occur over longer distances. While anecdotal evidence exists for fomite transmission, studies to date have been unable to isolate fomite infection from

TABLE 1 Design features conducive to the spread of COVID-19 in meatpacking plants.

| Condition | Specification | Relationship to COVID-19 | Source |
|---|---|---|---|
| Proximity | Shoulder to shoulder, within three feet | Crowding and social distancing are difficult | Molteni[26] |
| Orientation Gen Env | Shoulder to shoulder, face to face | Noise, louder speaking | Molteni[26]; Meatpacking Companies' job description |
| Humidity | Both low and high | Virus survives longer in both high and low relative humidity | CEBM[32] |
| Temperature | 25–50°F in process and chill areas | Lower temperatures prolong virus survival | CEBM,[32] CEBM,[33] Williams and Keener[34] |
| Shift length | 8–12 h | Longer hours can produce higher exertion and less mask compliance and fit | Molteni[26] |
| Ventilation | Poor | Low fresh air intake and flow allows for greater concentrations of the virus | CEBM[32] |
| Shared facilities | Lunch, break, and restrooms | Contact in areas where there is ongoing community transmission increases possibility of infection | CDC[36] |
| Shared transportation | Buses to and from the facility, carpooling | May increase risk among carpooling workers | CDC[36] |
| High touch areas | Handles, buttons, and railings in a plant | Without disinfection, high-touch and metallic surfaces may retain live virus for longer periods of time | Middleton et al.[23]; Waltenburg et al.[35] |
| Aerosols for cleaning | Use intense water to clean surfaces which can carry a dense production of aerosols combining dust, feathers, and feces | Potentially increased aerosol spread | Middleton et al.[23] |
| Diverse language, and cultural differences | Multilingual, people of color, immigrants, and people in relatively low-income families | A vulnerable workforce who are less able to leave poor working conditions | CEBM[32]; CEPR[37]; MPI[38,39] |

possible respiratory infection.[29] Most scientists now believe the predominant exposure pathway of COVID-19 is through droplets or aerosols.[1,40] With respect to transmission within an enclosed space, three important factors play an outsized role in determining the likelihood of transmission: the length of contact between individuals,[41] proximity between workers,[41] and adequate fresh air ventilation.[30] We discuss these further in the context of our model.

## 2.1 | Waterloo, Iowa

Waterloo, Iowa is home to the largest Tyson Foods pork plant in the United States, accounting for almost 4% of the US pork processing capacity.[42] The plant is also one of the largest employers in the city, employing around 2800 workers of its approximately 67,000 residents.[43] The workers at the Waterloo plant encompass a wide range of backgrounds, nationalities, and ethnicities. Many are immigrants or asylum seekers from nations such as Haiti, Burma, Bosnia, and Mexico. These communities were hit hard when COVID-19 began to spread.

From April to the end of May 2020, between 1500 and 1800 of Waterloo's 2800 workers were infected with the virus.[44] The outbreak at the Tyson Foods' Waterloo plant would ultimately end up claiming the lives of eight workers, Sedika Buljic, Félicie Joseph, Jim Orvis, Reberiano Garcia, Axel Kabeya, Isidro Fernandez, Jose Ayala, and one unnamed individual. The virus was likely introduced to the Waterloo facility when workers from a closed plant in Columbus Junction were bussed into work.[44,45] Within 2 weeks, the Waterloo plant reported one hospitalization and Governor Kim Reynolds issued a proclamation of disaster emergency—limiting public gatherings through April 30. Three days later, 20 public officials called upon Tyson Foods to close the plant temporarily. State officials also sent a formal complaint to OSHA.

By the time the facility closed on April 22, 2020, 182 out of 279 cases in Black Hawk County could be tied to the Waterloo pork processing plant (Figure 1). Similar to other outbreaks, infections originating from the plant would spread to the community through nursing homes. The Monday after the plant's closure, four employees, all of whom had direct links with the Tyson plant, and one resident of Western Home Communities, a senior center in Waterloo, would test positive for COVID-19. Before closure, the plant failed to follow guidelines issued by the Centers for Disease Control and Prevention (CDC) in early February 2020.[46,47] County officials touring the plant before closure indicated that precautions such as social distancing and wearing masks were not in place. Sheriff Thompson of Black Hawk County described a lack of communication between

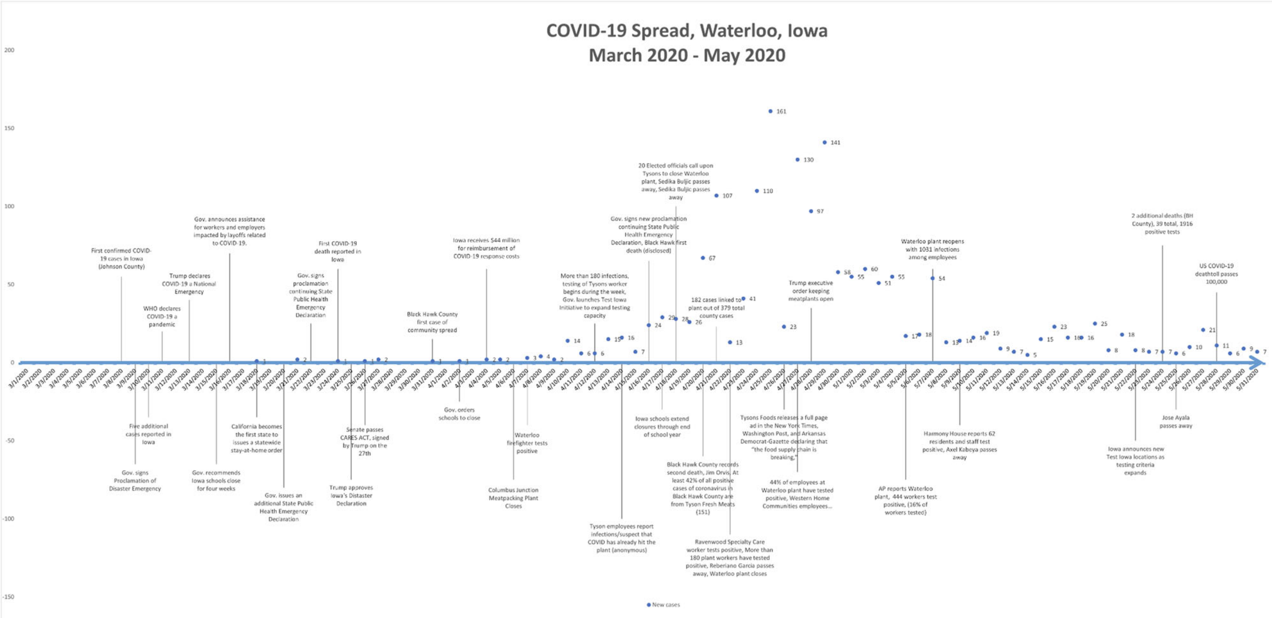


**FIGURE 1** COVID-19 in Tyson Foods meatpacking plant and Black Hawk County timeline. Blue dots represent the daily new COVID-19 cased along the timeline.

management and workers on how to wear masks. When the plant reopened on Thursday, May 7, 2020, the number of infections among its employees had already reached 1031. At the reopening, plastic barriers, personal protection equipment (PPE), multilanguage signage, and temperature checks were in place responding to pressure from local officials, community, and the national media.[47,48]

One major outstanding question that remains unanswered is whether additional mitigation measures would have abated or at least slowed the spread of the virus. While information on the geometry and key design features are not publicly available, we were able to construct a reasonable approximation with information from United States Department of Agriculture (USDA) and OSHA, and discussions with local officials. We then used an agent-based model (ABM) to simulate the movement of workers within the facility and the spread of COVID-19. With an ABM approach, we can model individual-level behavior and the transmission propagation to the system (in this case, the plant floor).[49] We are also able to integrate spatial features[50]; introduce randomness; model complex behavior between agents,[50,51] and finally incorporate different time scales to accurately capture temporal descriptions[52]; this is particularly useful in environments where many factors change simultaneously over time.[49]

ABMs have recently been used for assessing the effects of public mandates including containment and screening policies on disease spread[53]; the effect of social distancing policies on epidemiologic and economic outcomes,[54] and the use of genomic surveillance to estimate containment outcomes.[55] Other aspects related to transmission explored in ABM models include estimating the spread of COVID-19 associated with exposure time,[56] incubation time,[54,57] social-distancing,[57,58] infection probability,[59] and severity and death rate.[54] The models have performed well in settings where data are constrained or fine-grained estimation is appropriate, including within closed facilities.[59] We add to the larger pandemic literature by examining the spread of COVID-19 within an enclosed meatpacking facility. This application has significant relevance for managing food supply lines and worker safety thresholds in future pandemics.

## 3 | METHODS

To capture the dynamics of the floor processing lines in the meatpacking plants, while also focusing on the transmission patterns, we have developed the meatpacking plant geometry, basic agent parameters and used a number of reasonable assumptions to capture agent behavior. In this section, we describe the ABM specification and our mitigation scenarios.

### 3.1 | ABM model specification

We established modeling parameters for the infection probability, the transmission type, and temperature, humidity and ventilation (Table 2). The most commonly used infection probability in COVID-19 studies for confined public spaces is 2%,[29,60,61] although other studies show infection probability rates vary by age,[62] by ventilation rate,[60] and by proximity.[62] Comparisons of modeled versus observed infections suggests that coronavirus infection rates are between 2.5% and 4.2%.[61] Most ABM studies adopt a rate between 10% and 20%.[53,59] We were able to identify only two studies associated with meatpacking, with one paper indicating an infection probability of 9.1%,[35]

**TABLE 2** Indicators and assumptions adopted in the paper.

| Factor | Model parameters | Source |
|---|---|---|
| Infection probability | 1%–20% | [35, 53, 59–63] |
| Transmission type | Droplet and airborne | [30, 64] |
| Temperature | Low temperature | [23, 32, 34, 65, 66] |
| Humidity | Low and high relative humidity rates | [23, 33, 65, 66] |
| Ventilation | With ventilation, the infection risk is uniform within a space; also ventilation is typically very low positive airflow rates, meaning limited fresh air | [60, 67] |

and the other indicating a range between 2.0% and 43.5%.[63] We allowed the infection rate to range between 1% and 20% depending on the PPE scenario. As we note, the adoption of the 20% as the maximum reflects considerations of route of transmission, ventilation, and humidity and temperature.

We allowed for different routes of transmission. Two primary types of transmission channels occurred during the pandemic. The first, droplet transmission, is where large respiratory droplets (>5 µm) remain in the air, but only for a short time, with a travel distance less than 1 m (3.28 feet).[30,64] The second, airborne transmission, is defined as through virus-laden small aerosolized droplets (<5 µm), which remain in the air longer with a travel distance greater than 1 m. Studies find that the transmission of COVID-19 occurs primarily via the first channel where close contact or contaminated surfaces facilitate the infection,[60] and that the second channel is also viable for spread, depending on the concentration of the aerosolized droplets.[68] We captured the second in allowing transmission between close stationary workers; the interactions between stationary and nonstationary workers allow for droplet transmission.

Ventilation has a strong association with infection probability. To retain a 1% infection probability for 30 min of exposure of one susceptible person, a ventilation rate of 150 cubic feet per minute (cfm) is required per infector. A 3-h exposure requires a ventilation rate of 710–1420 cfm.[60] Under the same ventilation rate, the more infectors that stay in a facility longer the higher the probability of infection. Additionally, a study found that in a confined space such as restaurants, with only recirculated air, 10 out of the 30 people were infected during a mealtime period.[30] Meatpacking plants have at or less than a 0.11 air changes per hour (ACH) per hour positive airflow rate, which means very little fresh air is introduced into the plant.[67] With this rate, the 20% probability rate adopted in the model is reasonable to approximate plant ventilation characteristics.

Finally, we draw attention to the effect that relative humidity and temperature have on the size, scale and persistence of infectious particles, further influencing the transmission probability.[64] The virus survives longer in a lower temperature and in both high and low relative humidity environments.[23,32,65] Notably, a 1°C decrease in the minimum temperature is associated with an increase of 0.86 in the cumulative number of COVID-19 cases.[32]

### 3.1.1 | Plant geometry

Public access to a large meatpacking plant, like Tysons, is limited.[69,70] Plants are individually designed and while meeting recommended guidelines, may locate parts of the plant in different locations,[67,71,72] and the layout affects the efficiency of materials transport and the flow of materials.[34] We established the geometry of a 100 × 48 ft meatpacking plant taking advantage of Williams and Keener's work, which provides typical block process diagrams for poultry, pork, and beef processing facilities. Our base model used 42 inch spacing to separate workers in the processing areas and 48 inch spacing in the kill floor; the distance between the aisles of vertical workstations (Figure 2) is set to 6 ft (72 inch). We assigned the locations of workers based on the allowable spacing requirements between workers and aisles in different sections, and ensured that each individual worker had sufficient occupant area, which was approximately 100 $ft^2$.[34] Our model easily scales to a smaller or a larger plant size.

We specified two types of agents: healthy and infected and assign them to one of two types of working zones based on the workflow associated with processing operations. Certain sections, such as the fabrication and packing section, require intensive physical labor compared to activities in the kill and chilling sections.[71,73] We grouped the fabrication and packing (processing area and mixing and stuffing area) sections as one working zone and kill and chilling (holding cooler, prechill cooler) areas as another working zone. The real life operational functions of a plant are, of course, more complex. We reduced the complexity to flexibly model different scenarios.

We used NetLogo to design and simulate agent-based movement within our modeling geometry. The patch color indicates different spaces in the model: doors (purple), walls (black and white) and zone areas (Figure 2). Within the plant, the risk varies depending on where a worker is stationed. For example, the raw processing, further processing and kill floor sections have much higher transmission risks than cooling and retail sections, because it is difficult, if not impossible, to practice social distancing in the production lines and retain production capacity.[74] We specified high risk areas where workers are largely stationary (i.e., killing and processing) and low risk areas, where workers are moving between locations (chill area and breakrooms). We had two types of workers, healthy and infected. We designed the model to allow us to select different starting numbers for the worker population, initially infected workers, the time decay

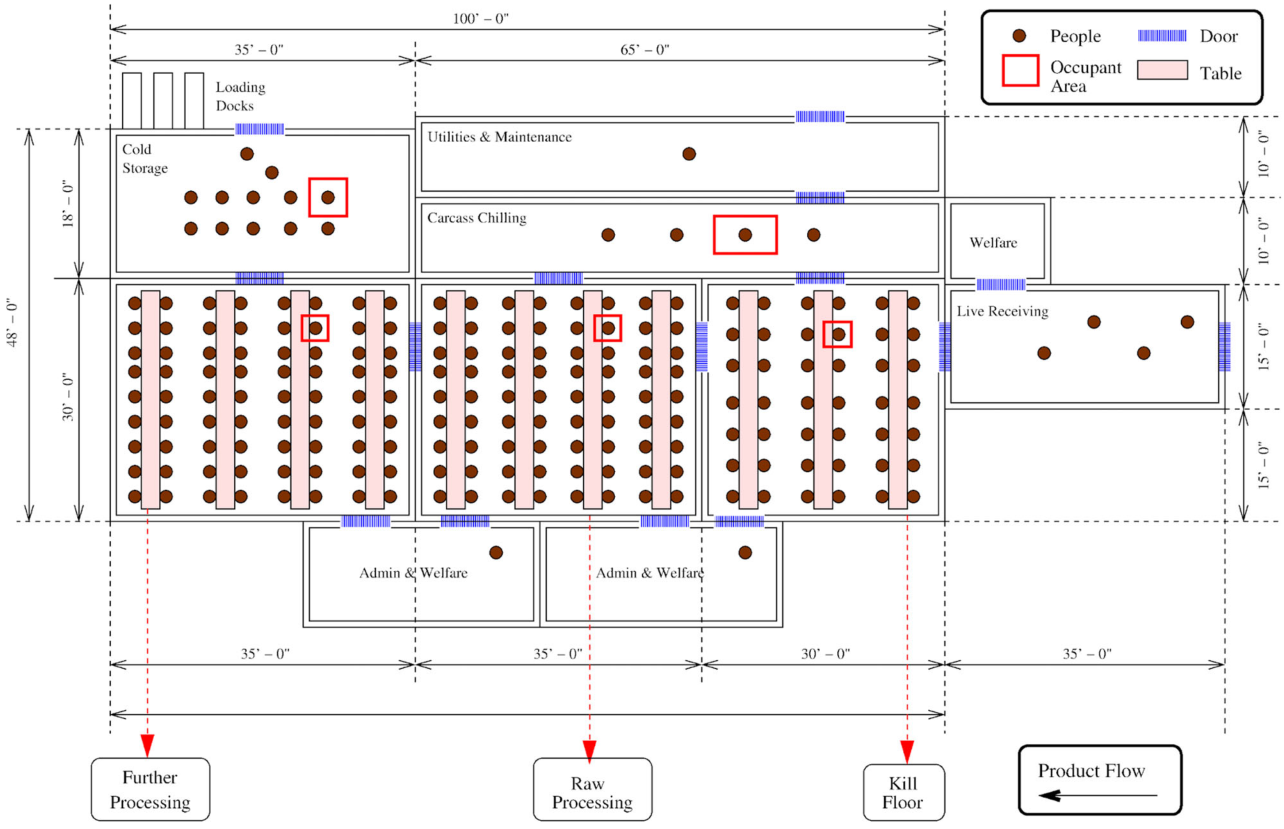


**FIGURE 2** A typical meatpacking plant plant-view. Workers in the further processing, raw processing as well as kill floor are mostly stationary workers, and nonstationary move within or between various sections.

period of virus remaining active on a surface (or patch), the nonstationary agent moving speed (in mph), and the infection probability (including direct person to person contact, person-to-surface contact, and stationary transmission). The CDC emphasized that one of the distinctive factors affecting COVID-19 exposure is prolonged proximity (i.e., for 10–12 h per shift) to other workers.[36] We assigned all nonstationary agents the same moving speed. This simplified the modeling for nonstationary workers, coheres well with the overall transmission modeling, and allowed for interactions between stationary and nonstationary workers. We placed the stationary workers in two processing sections as well as one kill section based on our plant geometry; workers are proximate to each other and have long contact duration in these lines.[36] Our model simulated a 12-h time period, which represented a single shift, and the model terminates when all workers were infected or the shift ends.

### 3.1.2 | Mitigation measures

In response to the outbreaks in the meatpacking plants, the CDC and the OSHA released voluntary guidance aimed at reducing the spread of COVID-19 among workers.[75,76] OSHA recommended two general strategies to mitigate against COVID-19. The first strategy recommended a worker safety protocol that includes encouraging sick workers to stay home; maintaining at least 6 ft of distance between workers; installing partitions along the production line; discouraging sharing of equipment and tools, and encouraging respiratory etiquette, including covering coughs and sneezes.[77]

OSHA's second strategy recommended implementing a hierarchy of controls from engineering and administrative controls to use of PPE. The engineering controls included modifying the alignment of workstations to increase the distance between workers, installing high-efficiency air filters, increasing ventilation rates in the work environment and installing physical barriers. Administrative controls included promoting social distancing, modifying processing or production lines and educating and training workers.

As meatpacking facilities began to close across the US and workers stayed home or got sick, Tyson Foods, JBS USA, Cargill, Sysco, and Smithfield Foods implemented some of these controls in an attempt to limit the spread of COVID-19 (Table 3). Using information from company websites, the following measures appeared to have been adopted at reopening: the use of physical and plexiglas barriers in workspaces and in communal transportation; the expansion of space available for breakrooms and lunchrooms (tents set up outside); provision of additional PPE with wear made mandatory; staggered shift and break times; temperature and screening questions before entering plants; restrictions on business travel as well as visitors to company facilities; waiving waiting periods for short-term disability; relaxed attendance policies; offered paid

**TABLE 3** Mitigation measures adopted by major companies.

| Mitigation measures | JBS USA Holdings | Cargill meat solutions | Tyson foods | Smithfield foods | Sysco Corp. | Our model |
|---|---|---|---|---|---|---|
| PPE | X | X | X | X | X | O |
| Physical barriers | X | X | X | X | | O |
| Social distancing | X | X | | X | | O |
| Testing | X | X | X | X | X | |
| Attendance and sick leave policies | X | X | | X | | |
| Increased sanitation | X | X | X | | | |
| Travel and visitor policies | X | X | | | X | |
| Carpool policies | | X | | | X | |
| Staggered break times | X | | | | | |

**TABLE 4** Scenario description of different mitigation measures.

| Parameters | Midway measures | Base 6 ft scenario | Current mitigation measures | Midway mitigation measures | Stringent mitigation measures |
|---|---|---|---|---|---|
| Infection probability | 20% | 20% | 5% | 5% | 1% |
| Social distance | No social distancing | 6 ft | No social distancing | 6 ft | 6 ft |
| Protected population | 0% | 100% | 100% | 100% | 100% |
| Infected workers ratio | 1:9 | 1:9 | 1:9 | 1:9 | 1:9 |
| Infection duration (min) | 30 | 30 | 30 | 30 | 60 |
| Population (stationary) | 186 | 93 | 186 | 93 | 93 |
| Population (overall) | 200 | 100 | 200 | 100 | 100 |

leave for workers in vulnerable populations, and increased cleaning. In our scenarios, we integrated those strategies known to reduce exposure based on the literature.

### 3.2 | Model scenarios

We modeled five scenarios (Table 4). In the base scenario, we created conditions reflecting our understanding of pre-covid conditions. This includes no social distancing, close working proximity, and no mask protection. We denoted this scenario pre-covid base. Our scaled plant geometry used 200 workers. We added to this scenario, a second base scenario that deploys 6 ft social distancing, which also required a reduction in the processing line workforce, thus affecting production output. These two scenarios represent base conditions.

We developed three additional scenarios reflecting the current mitigation, a midway scenario and a more stringent scenario. At reopening, plants relied on plastic barriers and surgical masks. We made two adjustments to our modeling to capture these measures. In the first, we increased the duration time to mimic the installation of plastic barriers.* In the second, we accounted for surgical masks. Surgical masks have an infection probability that varies between 3.5% and 20% among healthcare workers (HCWs)[†,78] and their laboratory-based efficacy is between 37% and 69%[79]; we were conservative and adopted a 5% infection rate for our model. Thus, our midway scenario captured social distancing and the use of surgical masks. Although surgical masks are not as effective as our infection rate would imply, we followed CDC's six-foot distancing recommendation to lessen infection likelihood. Finally, our stringent scenario combined social distancing and the use of N95 masks. The effectiveness of N95 masks is quite high compared to KN95 and surgical masks based on laboratory-based efficacy.[79] Wang's study in China examined the effectiveness of using N95 masks among health care workers in three hospitals, and found no infections for those using N95 masks.[80]

## 4 | RESULTS

### 4.1 | Base scenarios

Recall, our base model does not require social distancing and replicates worker conditions before the COVID-19 outbreak. The initial infection ratio is assumed to be 1:9 (or 10%) for both scenarios.

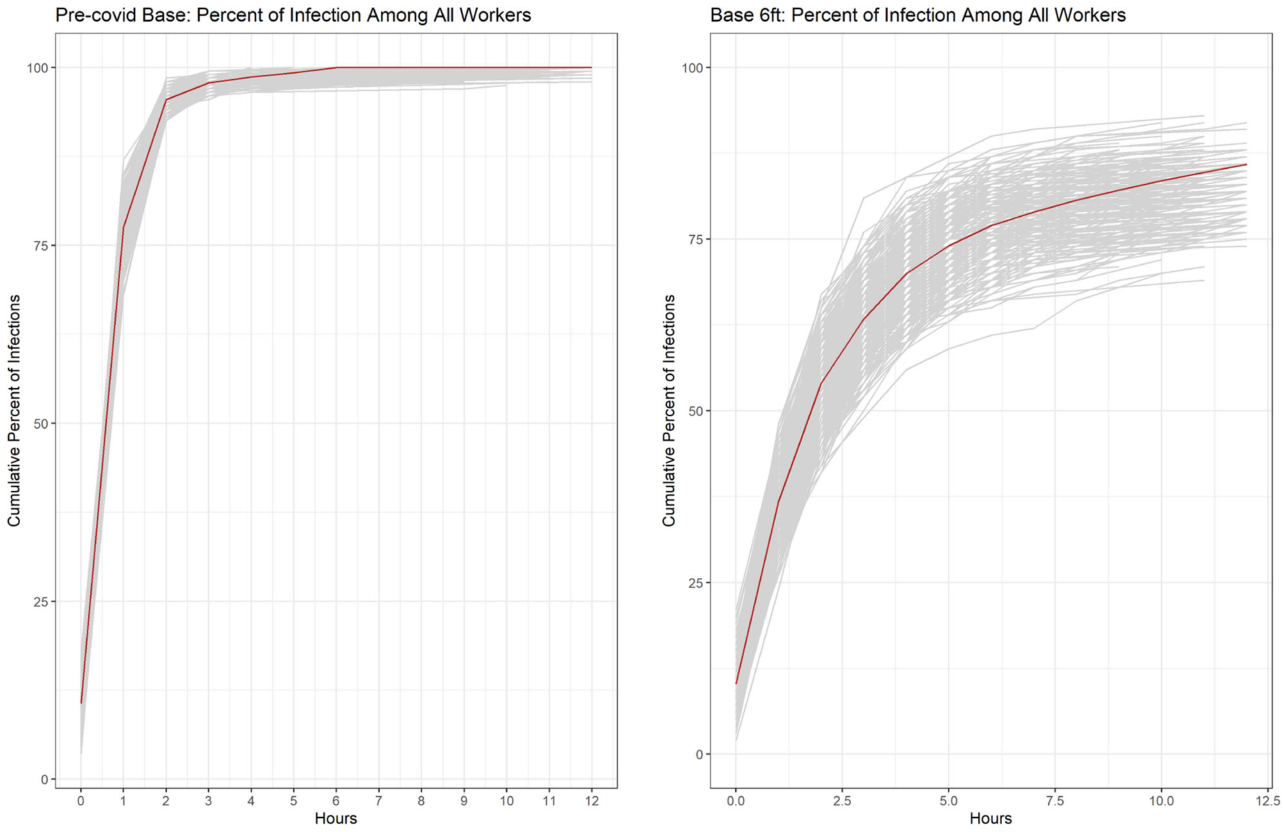


**FIGURE 3** Percent of cumulative infection among all workers for the pre-covid base scenario (left) and 6-ft base scenario (right). Gray lines represent the individual model simulations. The red line is the average over all simulations.

The pre-covid base starts with 20 infected agents and the 6-ft base starts with 10 infected agents at the beginning of each simulation. We simulated each model 500 times and the average number of workers infected are 199 out of 200 (99.3%) in the pre-covid base and 82 out of 100 (81.9%) in the 6-ft base (Figure 3). In other words, nearly every worker on the processing lines is infected by the end of the 12-h shift.

The left side of Figure 3 shows the cumulative percentages of infection for the 12-h shift for the pre-covid base and on the right side, the pre-covid 6-ft base. The red line in each plot is the average across all simulations; the gray lines reflect the results of each individual simulation. The pre-covid base model (left) simulations show low variability, with a steep infection rate within the first 2 h. Almost all agents were infected at the end of the 12-h simulation period. The pre-covid 6-ft base model (right) shows greater variation in the individual runs. For example, on any given shift, by hour five, there could be between 60% and 85% of workers infected. The simulation results show a minimum of at least a 60% infection rate for any given shift. The variation in the base 6 ft scenario was associated with the random assignment of infected status. If a high number of agents randomly assigned as infected were nonstationary, then infection rates would be higher. Low infection rates could happen when most of the initially infected workers were within a single stationary area (e.g., processing and kill sections).

## 4.2 | Mitigation scenarios

Here, we look at our three different mitigation scenarios: Current, Midway, and Stringent (Figure 4). The left side of Figure 4 depicts the cumulative percentage of infections among all workers for the 12-h shift. Among these five scenarios, as might be expected, the pre-covid base scenario resulted in the highest number of infected workers, while the most stringent scenario had the lowest. The right side of Figure 4 depicts the cumulative infection rates among those already infected. It provides another way of understanding infection rate among these five scenarios where the line steepness reflects the speed at which workers were infected. In the pre-covid base scenario, 85% of infected workers became infected in the first 2 h. In the current scenario, this level of infection took 3.5 h and in the stringent scenario, 85% of the infected workers were infected by 8.5 h. Mitigation measures reduced the number of workers infected (Figure 4, left side) and slowed the virus transmission (Figure 4, right side).

Looking at the effectiveness of the current mitigation (gray dotted line, masking and no distancing), the rate of infection approached the pre-covid base (red line) in 5 h. Not surprisingly, masks initially slowed the spread of the virus but over time and with workers in close proximity masks became less effective. It is also notable that the results of the 6-ft base scenario (distancing, no masks) and the midway mitigation measures (distancing and masks)

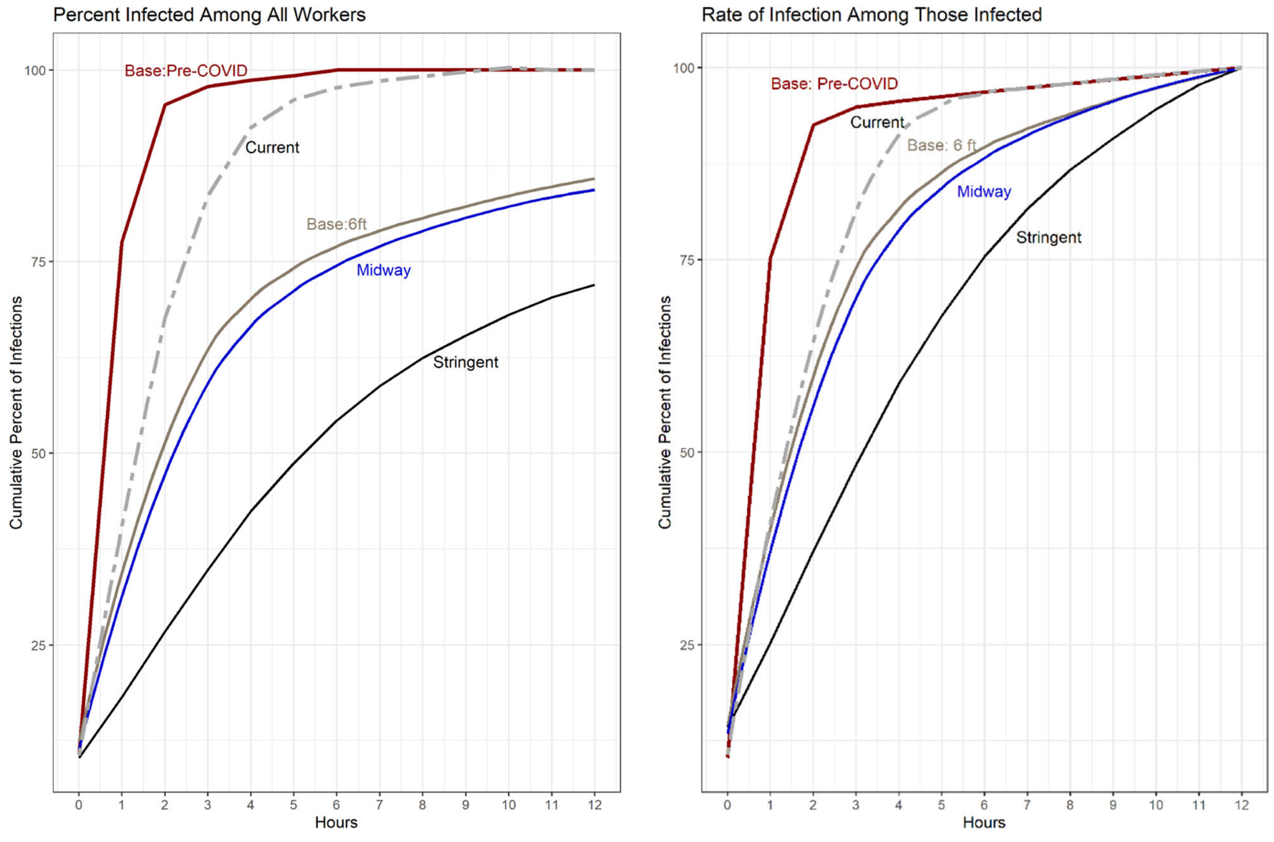


**FIGURE 4** Comparison of the average infection spread between scenarios.

produced similar results. The distance between these lines and the red and gray dotted line indicates that social distancing slowed down the initial spread of the virus, and retained some effectiveness over time. Finally, as might be expected, social distancing plus N95 masks (black line) resulted in the least amount of infection spread.

While our results were conceptually consistent with what was expected as mitigation measures become more stringent, it is also important to note that results were also more consistent with reported actual events[81] than outcomes reported by the industry. Our scenarios all showed high levels and rates of virus spread. When the plants shut down, nearly two-thirds of all plant workers had tested positive. The percent of workers testing positive alone was probably higher. Add to that a 25%–30% asymptomatic population [82,83] and our pre-covid base results were reasonable. Moreover, the continued rate at which workers were infected suggests that even with masks, the enclosed nature of the plant made our current and midway scenarios reasonable. Discussions with multiple sources and the general state of knowledge confirmed that the meatpacking facilities largely rely on recirculated air for ventilation.[67,71] Because of the way the ventilation systems operate, the plants serve as a nearly perfect incubator for the COVID-19 virus.[84] Consequently, as long as there were infected workers, even with the N95 masks, without improved circulation the infection rate was unlikely to trend downward to zero.

## 4.3 | Variations in mitigation scenarios

We provide the results of our simulations for each of the key mitigation scenarios (Figure 5). Overall, the three panels in Figure 5 show that the counts of infected workers against the infection timelines flattens as we move from less (current) to more worker protection (stringent). However, the range of potential outcomes from our three scenario simulations are very different. The outcomes for the current mitigation are consistent: the vast majority of workers eventually become infected. The range of uncertainty is less than 3%.

For midway mitigation measures, the results show greater variability in potential outcomes. The number of infected workers at the end of a simulated 12-h shift could range from 97% to 100% for the current scenario and as much as 41%–85% for the stringent scenario. Both midway and stringent scenarios required practicing social distancing, which lead to greater variation when comparing results to the current model (no social distancing). As we discussed previously, to a large degree this reflected the spatial position of initially infected workers. That is, when the simulation starts, if there were few to no infected workers in the largest area (raw and further processing), and social distancing was effective in flattening the curve, simulation outcomes would tend to be in the lower bound of the uncertainty range.

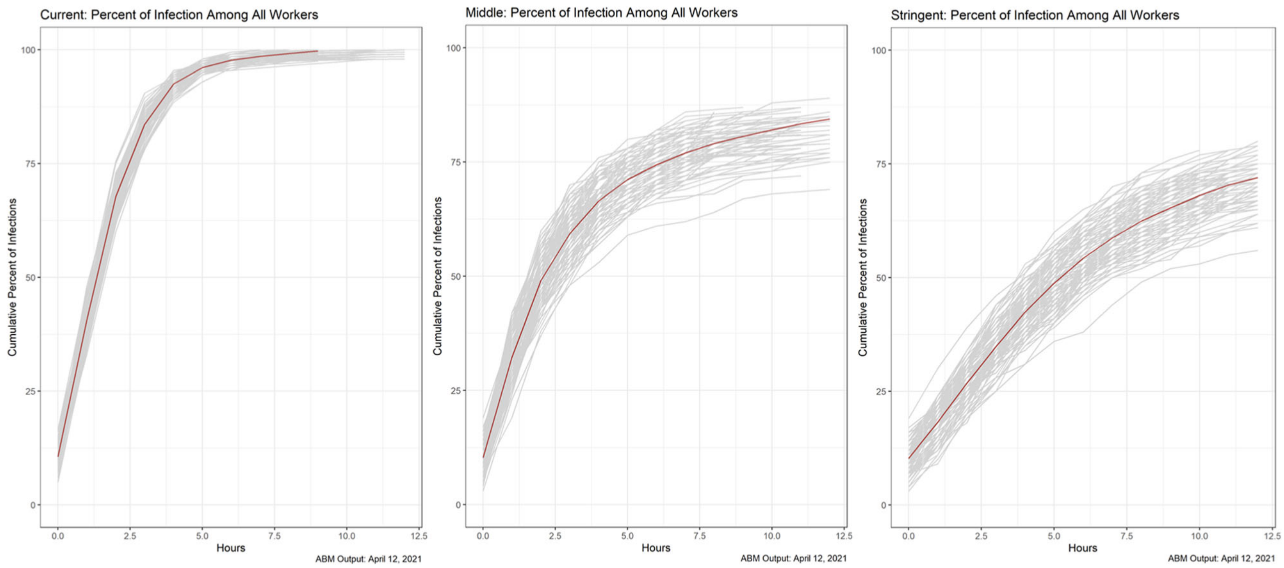


**FIGURE 5** Variations in current, midway and stringent scenario simulations. Gray lines represent the model simulations; red is the average over all runs.

## 5 | DISCUSSION

Our modeling results show that even under strict mitigation regimes, a high infectious rate persists. There were an average of 33 new cases per 100,000 workers per day reported in January 2021 in the meat and poultry sector and a reported 98 new cases per 100,000 workers per day in May 2020.[85,86] The outbreak waves reported in April 2020 and continuing through 2021[‡,87] diminished over time. However, despite high numbers of prior infections and falling incidence, plant workers remained at risk. New outbreaks persisted not only in the United States,[88] but also in other countries, including Canada[89] and Ireland.[90]

### 5.1 | Current facility design practice

There are two main issues with existing meat processing facilities that are associated with common design practices. The first is the use of a constant negative pressurized ventilation system. The negative pressure requirement prevents unfiltered contaminated outdoor airflow into an indoor facility, which can contaminate food packaging. Because of the negative pressure, most of the indoor air moving capacity is through large roof fans. In theory, such ventilation systems function based on the assumption that fresh outdoor air would flow one-way from relatively clean area (i.e., packaging) to locations with bioaerosols (i.e., killing area), then eventually to the exhaust fans (Heber, Zimmerman, Linton 2002). In reality, airflow is affected by many variables. The close proximity between killing and packing areas makes one-way clean to contaminated airflow difficult, increasing the potential for cross contamination. Under these conditions, bioaerosol exposure cannot be mitigated through social distance or plastic barriers; rather, it requires complete rethinking of the ventilation system design for a food processing facility.

The second issue is the fundamental design approach taken for these types of facilities in general. Most industrial facilities, including food processing, are designed to optimize production efficiency; there is limited ability to spatially redeploy workers to increase worker safety without affecting production output. In short, the facility layout design is treated as an arrangement to optimize the production of goods or the delivery of services, not ensure the health of workers.[91] Food safety and hygiene are considered and regulated; however, the safety and health of workers are not, resulting in poor working conditions, even before the coronavirus pandemic.[92]

### 5.2 | Efficacy of mitigation measures

Our modeling results indicate that current mitigation measures adopted by companies were insufficient to prevent COVID-19 spread. Plastic barriers were installed in lieu of CDC's recommendation for social distancing.[36,75] The companies argued that the process made it impossible to practice spacing without significant reductions in production.[75] However, our results show that practicing six-foot distancing would have at least slowed the virus spread. During a CDC investigation after the initial outbreaks in the plants, distancing was observed in the lunchroom, common areas, hallway, but not in the work locations, especially on harvest and production lines.[93,94] After the outbreaks, surgical masks were provided on a limited scale in the plants.[92] During the inspection, the CDC observed that masks were either worn incorrectly (covering only the mouth) or not worn at all. In the fabrication line, balaclavas were provided, but CDC observed that workers were constantly adjusting balaclavas with their hands.[93,94]

Other policies also likely contributed to the spread of the disease. For example, the Waterloo Plant had no sick leave policy initially and then when workers became sick, the plant transitioned to a bonus system to encourage workers to continue to come to work.[71] This is consistent with CDC observations that plant management in South Dakota offered a $500 bonus to employees who did not take sick leave ("responsibility bonus") between April, 2020 to May 1, 2020.[93,94] The financial status of meatpacking workers coupled with inadequate or even hostile sick leave policies ensures that workers continue to come to work even with symptoms of illness. This is a form of organizational injustice.[95]

OSHA practices also contributed to a decline in worker safety laws during the pandemic in a number of ways.[81] First, OSHA plant inspections occurred once every 6 months to a year in the pre-covid era. During the pandemic, OSHA minimized the number of on-site inspections, largely using phone or online interviews.[96,97] Second, OSHA had a choice about whether to implement rules or regulations to increase the worker safety during pandemic. OSHA elected to issue a set of recommendations and guidance, which were voluntary. Thus, companies were not required to adhere to them.[77,98] Finally, the fines for violating OSHA regulations are relatively insignificant,[69,70,99] and most of the violations apply to conditions before the guidance was issued,[100] which means that companies were very unlikely to receive any penalties related operational decisions during pandemic. According to a local official that we spoke with, the Tyson Foods plant received a fine of $1500 from OSHA after eight people died. Other sources confirm that the cost of improving the ventilation system would far exceed any fines the plant might receive.[71]

## 6 | CONCLUSION AND FUTURE WORK

Our study suggests that while social distancing is important to slow down the rate of infection, it is likely insufficient to prevent widespread transmission of COVID-19 in enclosed areas with poorly or narrowly designed ventilation systems. The infection rates in each of our five scenarios stayed high despite the mitigation measures. The pre-covid base scenario showed an average infection rate of 99% and the 6-ft distancing base scenario resulted in an infection rate of 82%. Even under the most stringent mitigation measures, we still observed an infection rate of approximately 71%. Nonetheless, mitigation measures do slow down the rate of infection. Our pre-covid base model indicated that 85% of the overall infected workers could be infected within the first 2 h. Under the current and stringent measures, it took 3.5 h and 8.5 h, respectively, for 85% of workers to be infected.

Cramped workspace, frigid temperature, poor ventilation, and long working hours with short, largely indoor breaks put meatpacking workers at a higher risk of contracting COVID-19.[26] More than 50,000 meatpacking workers were infected, with some 250 deaths across 38 states.[101] Others have noted that if workers of occupation are deemed essential, then basic health coverage and protection should be mandatory.[13] Urgent action is required across government agencies, companies, and local communities. OSHA's rules require updating, with targeting toward the likelihood of future pandemics. Government has long played an important role in shaping agricultural markets.[102] For companies, improving the ventilation system should be a high priority. Currently, design requirements call for 20 to 25 ACH for a food processing facility. These guidelines should be revised to reflect the new reality of respiratory infection potential.

The limitations of our research largely derive from data availability. Neither the meatpacking plants, nor the government agencies fully disclose data relevant to outbreaks to the public.[87,103,104] Although our assumptions are grounded in the literature, some clearly could be refined. In any case, we leave the question of how to improve data collection of COVID-19 for further research. We also adopted a model in which indicators (Tables 2 and 4) were static. This means, for example, that during a simulation the effectiveness of masks was the same over the 12-h period. This, as well as other indicators, could vary over the course of a simulation because we knew that effectiveness can deteriorate over time.

## AUTHOR CONTRIBUTIONS

**Jiehong Lou**: Study design; data acquisition; manuscript writing; results review; agree to be accountable for integrity/accuracy of the material. **Sachra Borjigin**: Conducted the agent-based modeling; participated in paper draft. **Connie Tang**: Constructed the timeline. **Yalda Saadat**: Collected information on OSHA guidelines. **Deb A. Niemeier**: Conceptualized the study; reviewed and conceptualized results; assisted in writing paper draft and provided final approval of draft; agree to be accountable for integrity/accuracy of the material.

## CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

## DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ETHICS APPROVAL AND INFORMED CONSENT

According to the University of Maryland Institutional Review Board, this study was exempt from review as interviewees were not considered research participants.

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## ENDNOTES

* We did not find any available data on the effectiveness of using plastic barriers.

† We were unable to find research comparing infection rates for different types of masks used in a meatpacking plant environment. We adopt the infection rates of the health care workers.

‡ The first plant is Tyson Foods and located in Nashville, Arkansas, three outbreak dates are 7/27/2020, 10/29/2020, and 1/25/2021; Second plant is Mission Foods in Pueblo, Colorado, and the corresponding outbreak dates are 6/17/2020, 12/3/2020, and 1/14/2021.

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