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ENVIRONMENTAL MICROBIOLOGY

Combined Infection Control Interventions Protect Essential Food Workers from Occupational Exposures to SARS-CoV-2 in the Agricultural Environment

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ABSTRACT Essential food workers experience elevated risks of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection due to prolonged occupational exposures in food production and processing areas, shared transportation (car or bus), and employer-provided shared housing. Our goal was to quantify the daily cumulative risk of SARS-CoV-2 infection for healthy susceptible produce workers and to evaluate the relative reduction in risk attributable to food industry interventions and vaccination. We simulated daily SARS-CoV-2 exposures of indoor and outdoor produce workers through six linked quantitative microbial risk assessment (QMRA) model scenarios. For each scenario, the infectious viral dose emitted by a symptomatic worker was calculated across aerosol, droplet, and fomite-mediated transmission pathways. Standard industry interventions (2-m physical distancing, handwashing, surface disinfection, universal masking, ventilation) were simulated to assess relative risk reductions from baseline risk (no interventions, 1-m distance). Implementation of industry interventions reduced an indoor worker's relative infection risk by 98.0% (0.020; 95% uncertainty interval [UI], 0.005 to 0.104) from baseline risk (1.00; 95% UI, 0.995 to 1.00) and an outdoor worker's relative infection risk by 94.5% (0.027; 95% UI, 0.013 to 0.055) from baseline risk (0.487; 95% UI, 0.257 to 0.825). Integrating these interventions with two-dose mRNA vaccinations (86 to 99% efficacy), representing a worker's protective immunity to infection, reduced the relative infection risk from baseline for indoor workers by 99.9% (0.001; 95% UI, 0.0002 to 0.005) and outdoor workers by 99.6% (0.002; 95% UI, 0.0003 to 0.005). Consistent implementation of combined industry interventions, paired with vaccination, effectively mitigates the elevated risks from occupationally acquired SARS-CoV-2 infection faced by produce workers.

IMPORTANCE This is the first study to estimate the daily risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection across a variety of indoor and outdoor environmental settings relevant to food workers (e.g., shared transportation [car or bus], enclosed produce processing facility and accompanying breakroom, outdoor produce harvesting field, shared housing facility) through a linked quantitative microbial risk assessment framework. Our model has demonstrated that the elevated daily SARS-CoV-2 infection risk experienced by indoor and outdoor produce workers can be reduced below 1% when vaccinations (optimal vaccine efficacy, 86 to 99%) are implemented with recommended infection control strategies (e.g., handwashing, surface disinfection, universal masking, physical distancing, and increased ventilation). Our novel findings provide scenario-specific infection risk estimates that can be utilized by food industry managers to target high-risk scenarios with effective infection mitigation strategies, which was informed through more realistic and context-driven modeling estimates of the infection risk faced by essential food workers daily. Bundled interventions, particularly if they include vaccination, yield

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significant reductions (>99%) in daily SARS-CoV-2 infection risk for essential food workers in enclosed and open-air environments.

KEYWORDS COVID-19, quantitative microbial risk assessment (QMRA), vaccinations, nonpharmaceutical interventions (NPIs), produce industry worker

Essential food worker populations have been disproportionately affected by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) illness and death (1–5). For instance, Canadian migrant farmworkers experienced a 20-fold higher incidence of SARS-CoV-2 infections relative to the general population (July 2020) (6). Similarly, food and agricultural workers in California, USA, experienced a 39% increase in excess mortality compared to a 12% increase for workers in nonessential sectors (March to November 2020) (7). Workplace practices such as close proximity and long shifts may be contributing factors to this increased infection risk (1, 8). Additional environmental exposures may occur among food workers during shared transportation (carpooling, work bus) (9–11) and in employer-provided housing (e.g., crowding, poor ventilation) (12–18). For example, a 2022 study found that of nearly 2.5 million confirmed SARS-CoV-2 infections in the Czech Republic, 27% of the infections originated either from work-related causes or contacts, while 73% originated from out-of-work contacts, with food workers noted as one of the highest incidence populations (19). Protecting essential food workers from SARS-CoV-2 is necessary to reduce the burden of disease among this often understudied and marginalized population and to ensure stability in the global food supply chain (20–22).

Global agricultural organizations (Food and Agriculture Organization of the United Nations, U.S. Department of Agriculture) and food trade associations (Global Cold Chain Alliance, American Frozen Food Institute) have recommended integrating SARS-CoV-2 infection control strategies (e.g., distancing, masking, symptom screening, vaccination, ventilation) to reduce transmission among food workers (23–27). However, despite the demonstrated effectiveness of these interventions among the general population during short-duration activities, their impact on protecting essential food workers during extended-duration (e.g., a whole day) activities has been poorly characterized (28–37). For example, outdoor seasonal and migratory workers involved in produce production, harvest, and processing have extended SARS-CoV-2 exposure during their daily activities (e.g., field harvesting, shared transportation, crowded employer-provided housing) (38–40). To our knowledge, there are limited studies quantifying the impact of SARS-CoV-2 infection control strategies to reduce transmission among food workers. One study, within a pork processing plant, found that SARS-CoV-2 PCR screening averted 7 to 40% of clinical SARS-CoV-2 cases among food workers (41). A second study, for indoor food workers, found that multiple SARS-CoV-2 infection control strategies (masking, distancing, vaccination) reduced worker infection risk below 1.0% within an indoor food processing and packaging environment (42). A third study, for indoor cold-chain food workers, found that standard SARS-CoV-2 infection control strategies (masking, distancing, vaccination) protected food workers from fomite-mediated transmission during indoor cold-chain packaging and transport activities (43). These studies focused on an indoor environment and only the processing or packaging activity but did not consider the outdoor environment or other daily food worker activities (e.g., field harvesting, shared transportation, crowded employer-provided housing) that may heighten SARS-CoV-2 infection risk among produce workers, including seasonal and migratory workers.

To address this need, the purpose of this study was to evaluate the impact of combined food industry interventions and worker vaccinations on reducing the daily cumulative risk of SARS-CoV-2 infection from occupational exposures to SARS-CoV-2 in the agricultural environment. Using a novel modular stochastic quantitative microbial risk assessment (QMRA) approach, we characterized the cumulative risk of SARS-CoV-2 infection across sequential environmental scenarios experienced daily by both indoor and outdoor food workers. This novel QMRA approach was then used to quantify the effect of individual and combined risk mitigation interventions at reducing SARS-CoV-2 infection risk across all indoor and outdoor scenarios. The findings of this work can be used by the produce industry to protect the

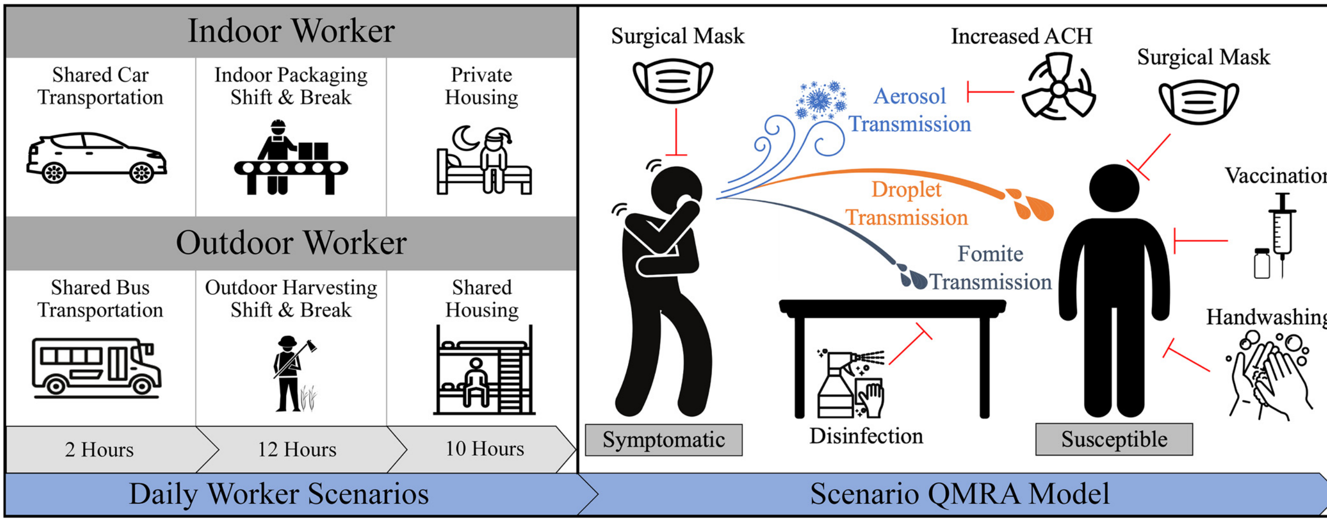

FIG 1 Environmental scenarios affecting daily cumulative risks of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) exposure for an indoor and outdoor produce worker. (Left) Daily worker scenarios. Simulations were conducted in which workers were engaged in three overarching environmental scenarios: 2 h of shared transportation to and from work (aerosol exposure only), a 12-h working shift (aerosol, droplet, fomite exposure), and 10 h of private (no exposure) or shared housing (aerosol, droplet, fomite exposure). (*Top left*) The indoor worker was assumed to travel in the back of an enclosed, midsized car for 2 h total with an infectious symptomatic passenger seated in front of them, allowing for exposure to virus-containing aerosols. During the indoor work shift, the uninfected susceptible and infectious symptomatic worker were assumed to spend 11 h physically distanced (2 m) while working on a conveyor line, with 1 h spent in an indoor breakroom. The indoor worker was assumed to not participate in shared housing. (*Bottom left*) The outdoor worker was assumed to travel in an enclosed school bus for 2 h total with an infectious symptomatic passenger seated >3 m away from the uninfected susceptible worker, allowing for exposure to virus-containing aerosols. Given the nature of the outdoor work shift, the uninfected susceptible and infectious symptomatic workers were assumed to spend 11 h in close-contact range (1 m) while working in the open-air harvesting field, with 1 h spent on the school bus functioning as a breakroom. The outdoor uninfected susceptible worker was assumed to participate in employer-provided shared housing for 10 h with an infectious symptomatic co-worker. Of the 10 h, it was assumed that the workers would spend 2 h physically distanced (2 m) in the space, while the remaining 8 h would be spent sleeping in the same room (aerosol exposure only). (Right) Scenario quantitative microbial risk assessment (QMRA) model. Each scenario simulates the risk of SARS-CoV-2 infection for an uninfected and susceptible worker after exposure to an infected and symptomatic co-worker across viral transmission (aerosol-, droplet-, and/or fomite-mediated) pathways. Each scenario also quantifies the impact of infection control strategies (red lines), adjusted for the context of each scenario. For example, universal masking (defined as both workers wearing the same type of mask) was applied to both the infected and susceptible worker, increased air exchange and surface disinfection was applied to the modeled environmental scenario, and both the hand hygiene and vaccination interventions were applied to the susceptible worker alone (see Materials and Methods). ACH, air exchange rate.

health and well-being of this essential workforce from infection comprehensively across daily, rather than solely one-time, exposure to SARS-CoV-2 and future novel respiratory pathogens.

RESULTS

Scenario-specific and cumulative daily SARS-CoV-2 infection risks for an indoor produce worker with and without infection control measures. We investigated the individual and cumulative SARS-COV-2 infection risk to a susceptible indoor produce worker (Fig. 1) across four daily scenarios: shared car transportation (2 h), an indoor facility work shift (11 h), break in the indoor facility breakroom (1 h), and private housing (10 h). With no infection control strategies applied, the lowest-risk scenario was the indoor breakroom (Table 1), whereas the highest-risk scenario was at 1-m distancing during the enclosed work shift. In the 11-h work shift scenario, the relative risk decreased by 47% when the distance was increased between workers from 1 m (1.00) to 2 m (0.530). However, due to the other daily exposures, the 24-h daily cumulative risk remained above 0.86 for both 1- and 2-m work shift distancing. After implementing individual infection control strategies across each modeled scenario, for the 24-h daily cumulative risk at 1 m, universal double masking resulted in the greatest relative risk reduction of 62%, while surgical masking reduced the risk by 22%, and cloth masking by 10%. For the 24 h daily cumulative risk at 1 m, increasing ventilation rates across each scenario resulted in a 8% relative risk reduction, while hourly handwashing and surface disinfection twice during the work shift provided no relative risk reduction (0%). The 24-h daily cumulative risk at 2 m was lower for each intervention assessed compared to the 24-h daily cumulative risk at 1 m.

TABLE 1 Cumulative risk and risk reduction of SARS-CoV-2 infection for indoor workers[a]

		Work shift distancing				Daily cumulative risk[b]	
Infection control strategy	Shared car transportation	1 m	2 m	Break in breakroom	Private housing	1-m distancing	2-m distancing
None[c]	0.698 (0.356 to 0.955)	1.00 (0.983 to 1.00)	0.530 (0.246 to 0.850)	0.024 (0.009 to 0.058)	None	1.00 (0.995 to 1.00)	0.865 (0.571 to 0.992)
Handwashing and surface disinfection[d]	No	1.00 (0.00%)	0.426 (19.7%)	No	None	1.00 (0.00%)	0.833 (3.78%)
Cloth mask[d]	0.163 (76.7%)	0.866 (13.4%)	0.148 (72.0%)	No	None	0.896 (10.4%)	0.303 (65.0%)
Surgical mask[d]	0.108 (84.5%)	0.749 (25.1%)	0.076 (85.7%)	No	None	0.785 (21.5%)	0.186 (78.6%)
Double mask[d]	0.025 (96.4%)	0.332 (66.8%)	0.025 (95.3%)	No	None	0.378 (62.2%)	0.058 (93.3%)
Increased air exchange[d]	0.126 (81.9%)	0.904 (9.64%)	0.081 (84.7%)	0.004 (81.7%)	None	0.923 (7.74%)	0.217 (75.0%)

[a]The table shows the cumulative risk and risk reduction (%) of SARS-CoV-2 infection for a susceptible indoor produce worker exposed to an infected co-worker. "No" indicates that the infection control strategy was not applied (see Methods). "None" means that there was no risk of infection in the private housing scenario. SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

[b]Assuming there is contact between an infected and susceptible individual in every environmental scenario except for private housing.

[c]The values represent median (95% uncertainty interval) SARS-CoV-2 infection risk.

[d]The values represent median (% reduction) SARS-CoV-2 infection risk compared to no infection control strategy.

Scenario-specific and cumulative daily SARS-CoV-2 infection risks for an outdoor produce worker with and without infection control measures. Next, we investigated the individual and cumulative infection risk to a susceptible outdoor food worker (Fig. 1) across four daily scenarios: shared bus transportation (2 h), an outdoor field work shift (11 h), a rest break in the bus (1 h), and shared housing (10 h). Without infection control measures, the lowest-risk scenario was at the 2-m distance during the outdoor field work shift (Table 2), whereas the highest infection risk was the outdoor field shift at 1-m distancing. In the 11-h outdoor work shift, the relative risk decreased by 97% when the distance was increased between workers from 1 m (0.322) to 2 m (0.009). However, due to the other daily exposures, the 24-h daily cumulative risk remained above 0.21 for both 1- and 2-m distancing. After implementing individual infection control strategies across each modeled scenario, for the 24-h daily cumulative risk at 1 m, universal double masking resulted in the greatest relative risk reduction of 92%, while surgical masking reduced the risk by 84%, and cloth masking reduced the risk by 77%. For the 24-h daily cumulative risk at 1 m, increasing ventilation rates in the shared bus transportation and shared housing scenarios resulted in a 15% relative risk reduction, while hourly handwashing and surface disinfection twice during the 11-h outdoor work shift provided a nominal relative risk reduction of $<$1%. The 24-h daily cumulative risk at 2 m was lower for each intervention assessed compared to the 24-h daily cumulative risk at 1 m.

Impact of combined infection control strategies and vaccination on the daily cumulative risk of SARS-CoV-2 infection for essential produce workers. We then investigated the impact of combined infection control measures with and without vaccination on the daily cumulative SARS-CoV-2 risk for the indoor produce worker (Fig. 2, left). Without vaccination, combining hand hygiene, surface disinfection, universal surgical mask usage, physical distancing to 2 m, and increased ventilation strategies across the indoor work scenarios reduced the relative daily infection risk by 98.0% for the indoor worker (0.020; 95% uncertainty interval [UI], 0.005 to 0.104) compared to the baseline risk at 1 m (1.00; 95% UI, 0.995 to 1.00). These combined infection control measures were found to be more effective than vaccination alone (72.1 to 92.4% suboptimal and optimal vaccination relative risk reduction, respectively). Combining infection control strategies with vaccination further reduced the relative daily infection risks between 99.5 and 99.9% for the indoor worker (suboptimal vaccine, 0.005 [95% UI, 0.001 to 0.035]; optimal vaccine, 0.001 [95% UI, 0.0002 to 0.005]). We also investigated the impact of these combined infection control measures with and without vaccination on the daily cumulative infection risk for the outdoor produce worker (Fig. 2, right). Combining hand hygiene, surface disinfection, universal surgical mask usage, physical distancing to 2 m, and increased ventilation strategies across the applicable outdoor worker scenarios reduced the relative daily infection risk by 94.5% (0.027; 95% UI, 0.013 to 0.055) compared to the baseline risk at 1 m (0.487; 95% UI, 0.257 to 0.825). Combining infection control strategies with vaccination further reduced the relative daily infection risks between 98.5 and 99.6% for the outdoor worker (suboptimal vaccine, 0.007 [95% UI, 0.003 to 0.018]; optimal vaccine, 0.002 [95% UI, 0.0003 to 0.005]). For both the indoor and outdoor worker, the combined infection control measures and vaccinations led to an absolute daily risk of $\leq$0.002.

Sensitivity analyses. Spearman rank correlation coefficients were calculated for each scenario to identify the parameters that were the most influential to the final SARS-CoV-2 exposure dose estimate. Across all scenarios, the parameters identified as most influential at *increasing* virus exposure were the viral shedding rate per hour (ρ_{avg} = 0.94), the infected worker's salivary virus concentration (ρ_{avg} = 0.85), and the coughing frequency (ρ_{avg} = 0.34). The parameters identified as most influential in *decreasing* virus exposure across all scenarios were the infected worker's double masking ($\rho_{avg} = -0.74$), the susceptible worker's surgical masking ($\rho_{avg} = -0.69$), and the susceptible worker's cloth masking ($\rho_{avg} = -0.55$). The car transportation and outdoor work shift scenarios were found to be affected the most by parameter variability, with overall variability ratios calculated to be 4.24 (aerosol transmission) and 4.48 (droplet transmission), respectively. Finally, the overall uncertainty ratio, representing the combined effect of parameter variability and uncertainty, was largest for the viral dose on a susceptible worker's hand (6.13) and the Brownian diffusivity (4.29) calculated for

TABLE 2 Cumulative risk and risk reduction of SARS-CoV-2 infection for outdoor workers[a]

		Work shift distancing				Daily cumulative risk[b]	
Infection control strategy	Shared bus transportation	1 m	2 m	Rest break in the bus	Shared housing	1-m distancing	2-m distancing
None[c]	0.010 (0.003 to 0.032)	0.322 (0.097 to 0.779)	0.009 (0.004 to 0.021)	0.012 (0.005 to 0.029)	0.189 (0.074 to 0.415)	0.487 (0.257 to 0.825)	0.216 (0.096 to 0.445)
Handwashing and surface disinfection[d]	No	0.320 (0.56%)	0.008 (13.1%)	No	No	0.486 (0.25%)	0.215 (0.49%)
Cloth mask[d]	0.001 (85.4%)	0.056 (82.7%)	0.002 (81.0%)	No	0.034 (82.1%)	0.112 (77.1%)	0.051 (76.5%)
Surgical mask[d]	9.5×10^{-4} (90.7%)	0.035 (89.1%)	0.001 (86.8%)	No	0.024 (87.3%)	0.080 (83.7%)	0.040 (81.6%)
Double mask[d]	2.2×10^{-4} (97.8%)	0.009 (97.1%)	3.7×10^{-4} (95.9%)	No	0.009 (95.3%)	0.038 (92.2%)	0.024 (89.0%)
Increased air exchange[d]	0.006 (45.3%)	NA	NA	No	0.101 (46.4%)	0.413 (15.1%)	0.128 (40.8%)

[a]The table shows the cumulative risk and risk reduction (%) of SARS-CoV-2 infection for a susceptible outdoor produce worker exposed to an infected co-worker. "No" indicates that the infection control strategy was not applied (see Methods). "NA" means that it is not applicable to apply increased air exchange in an outdoor environment. SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.
[b]Assuming there is contact between an infected and susceptible individual in every worker scenario.
[c]The values represent median (95% uncertainty interval) SARS-CoV-2 infection risk.
[d]The values represent median (% reduction) SARS-CoV-2 infection risk compared to no infection control strategy.

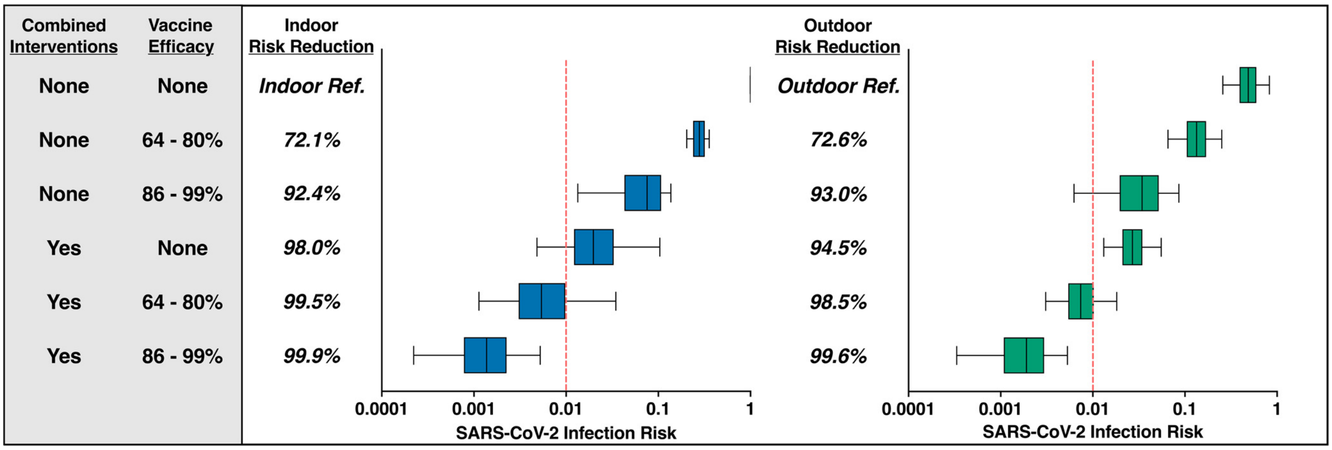

FIG 2 Essential produce workers experience the greatest reduction in SARS-CoV-2 infection risk when vaccinations are applied in combination with recommended infection control strategies. The combined interventions column represents simultaneous surgical mask usage, hourly handwashing, surface disinfection (twice per work shift), increased physical distancing to 2 m, and an increased air exchange rate per scenario. Within the vaccine efficacy column, the 64 to 80% vaccine efficacy range represents the suboptimal vaccine, while the 86 to 99% vaccine efficacy represents the optimal vaccine, both of which represent a worker's level of immunity to any infection, asymptomatic or symptomatic (see Materials and Methods for details). Relative risk reductions were calculated by comparing the risk estimate per intervention scenario against the baseline (no intervention, 1-m work shift distance) risk estimate. The top row represents the baseline (reference) daily cumulative infection risk for an indoor (left) and outdoor (right) produce worker across the 2 h of shared transportation, 12-h work shift at 1 m, and 10 h of shared housing scenario (outdoor worker only) with no infection control strategies applied. The median risk of infection is denoted by the line within each box plot, with error bars representing the 95% uncertainty interval. Finally, a vertical line has been added to denote a 24-h infection risk of 1.0%.

aerosol particle exposure. Please see supplemental material for additional details on sensitivity analyses (Fig. S2A and B and S3A and B) or uncertainty (Table S3).

DISCUSSION

The goal of this study was to estimate the impact of recommended infection control interventions on the daily cumulative SARS-CoV-2 infection risk to produce workers (i.e., working in an indoor facility or open outdoor farm) when exposed to various environmental scenarios (i.e., 1- or 2-m distancing, shared transportation, with or without shared housing). Among the environmental scenarios assessed for an indoor worker, we found the highest risk to be associated with the 1-m distancing indoor work shift, followed by shared car transportation. For an outdoor worker, the highest risk was associated with the 1-m distancing outdoor work shift, followed by shared housing. When evaluating the scenario-specific impact of each infection control intervention, we found that double masking provided the greatest protection for the indoor worker, while increased physical distancing between workers provided the greatest protection for outdoor workers. However, the greatest reduction (>99%) in daily SARS-CoV-2 infection risk (≤0.002) was observed when the combined infection control interventions were paired with optimal SARS-CoV-2 vaccinations for both indoor and outdoor workers. Despite elevated SARS-CoV-2 exposures throughout daily produce worker activities, these results suggest that current risk mitigation strategies, when implemented together, can effectively protect essential food workers from infection.

Our findings for the indoor packaging facility and outdoor harvesting field are consistent with data from well documented outbreaks across multiple farms and food processing facilities globally (1, 2, 22, 44, 45), which have highlighted the increased duration of contact and close proximity of workers on assembly lines as factors contributing to an elevated infection risk. In our study, one contributing factor for this elevated risk is likely the extended exposure duration (11-h work shift and 1-h break) to a coughing infected worker compared to other scenarios for which exposure durations are in the 1- to 2-h range. We also explored the impact of physical distancing during the work shifts and found that in the indoor facility and outdoor field, increasing the distance between workers from 1 to 2 m provided a 47.0% (indoor) and 97.2% (outdoor) relative reduction in infection risk. Consistent with modeling work by Wei and Li (46), there is an attenuation in distance traveled by respiratory particles with increasing size: small-diameter (<50 μm) respiratory aerosols can travel beyond 4 m after coughing, whereas 99% of large-diameter droplets (>100 μm) fall to adjacent surfaces within 2 m of their point of origin. As demonstrated here and in our previous modeling work, increasing the distance between workers allows for a shift in the predominant transmission route from close-contact droplets and aerosols to exclusively aerosols ($<$50 μm; responsible for 1.3% of expelled viral dose), further exemplifying the importance of physical distancing to reduce infection risk (42).

The elevated infection risk found in the shared car transportation scenario is consistent with the work of Ng et al. (47), who found that sharing a vehicle with an individual infected with SARS-CoV-2 was associated with a 3.05-fold increase in the odds of infection. This finding is likely due to the relatively low volume of air space (2.6 m^3) within the car, combined with the elevated persistence of infectious aerosols over multiple hours (48). For example, after increasing the volume inside the modeled car by 3-fold to 7.8 m^3 and keeping all other parameters constant, we observed a 55.4% reduction in the 2-h infection risk (0.311; 95% UI, 0.130 to 0.616) attributed to volume alone. Given our assumption of a well mixed environment in which the persistent aerosol particles are homogeneously distributed, one would expect aerosol exposures and subsequent infection risks to decrease as the air volume within the scenario increases. Similarly, conditions such as poor ventilation and small, enclosed employer-provided housing have been reported in various outbreaks among outdoor produce workers (14–18). For example, in July 2020, a California farmworker housing facility with five workers per room documented a 204-person SARS-CoV-2 outbreak (49). As others have reported (50–53), the smaller the size of the enclosed space and the more individuals in that space, the greater the risk of SARS-CoV-2 transmission. Taken together, these scenarios highlight the interconnected relationship between duration of exposure, distancing between individuals, and the size/volume of the enclosed space on SARS-CoV-2 infection risk.

Increased ventilation, relative to other infection control strategies, resulted in the greatest relative reduction in daily infection risk for an indoor worker (75.0% reduction at 2 m), while double masking provided the largest protective effect for both indoor (93.3% reduction at 2 m) and outdoor workers (92.2% reduction at 1 m). Our findings are consistent with the increasing evidence that higher ventilation rates, when applied appropriately and without recirculation, can reduce SARS-CoV-2 exposure and subsequent infection risk (54–57). Mechanistically, the overall airborne concentration of virus-containing particles can be reduced through natural or mechanical increases in ventilation rates, thereby reducing the viral dose exposure to a susceptible worker (36). An important limitation to this intervention has been noted by Lee and Ahn (55), who found that even at high ventilation rates of 20 h^{-1}, this intervention could not overcome the high infection risk associated with an infected and susceptible worker sustaining contact in small, enclosed office spaces (20 m^3). This suggests that larger facilities, like the indoor packing facility modeled here (460 m^3), would likely see a greater reduction in SARS-CoV-2 infection risk upon increasing their ventilation rate, compared to a smaller facility or office spaces.

Consistent with numerous laboratory (58–60) and empirical (28, 61) studies testing risk reductions associated with wearing face masks, our findings demonstrate that masks are an effective tool for reducing SARS-CoV-2 infection risk. Of the masks modeled, double masking (surgical mask followed by cloth mask) provided the greatest relative reduction in daily risk, followed by surgical and cloth masks. Given the increased transmissibility of newer SARS-CoV-2 variants (Delta: B.1.617.2; and Omicron: B.1.1.159 [62, 63]), the CDC has recently revised masking recommendations and has transitioned from promoting double masking to now promoting N95 and KN95 respirators, while surgical masks continue to be recommended for industry by Occupational Safety and Health Administration (OSHA) (64–66). After incorporating the universal usage of optimally fit N95 respirators (58) throughout our model (data not shown), the 24-h daily cumulative risk at 1 m for an indoor (0.033; 95% UI, 0.013 to 0.098) and outdoor (0.016; 95% UI, 0.007 to 0.033) produce worker was reduced by 96.7 and 96.8%, respectively. Given the documented facemask accessibility issues faced by produce workers at the onset of the pandemic (67, 68), the implementation of N95 respirators, though of superior risk reduction, is likely not feasible in this occupational setting.

However, our findings support the promotion of double masking in these occupational scenarios to further minimize infection risk beyond the use of cloth or surgical masks alone.

Our work provides novel insight into the effectiveness of combining vaccination with food industry-recommended infection control strategies to mitigate daily SARS-CoV-2 infection risk among essential produce workers. As demonstrated with the agent-based modeling studies of Farthing and Lanzas (69) and Kerr et al. (70), while individual interventions (e.g., physical distancing, masking, vaccinations, symptomatic testing, etc.) provided modest reductions in the expected number of SARS-CoV-2 infections, implementing multiple interventions simultaneously provided synergistic reductions in expected infections. It is important to note that this multipronged approach assumes absolute compliance with the interventions described; however, the layering of risk reduction practices is not new to the produce industry (71). As demonstrated by Mogren et al. (72), the "hurdle approach" of enforcing multiple risk reduction strategies with variable degrees of compliance can provide greater reductions in risk than a single intervention with poor compliance.

The strengths of our model include a detailed exposure assessment designed to simulate the environmental scenarios experienced daily by indoor and outdoor produce workers through a linked-modeling approach, vetting by academic and food industry partners to inform and endorse the design of our modeled environmental scenarios, and a versatile modeling framework that can be leveraged to evaluate novel SARS-CoV-2 strains or future respiratory pathogens and additional settings outside the food production and processing industry. To our knowledge, this is the first QMRA for SARS-CoV-2 that has established a linked-modeling approach to quantify the risk of infection both within and across a variety of environmental scenarios to estimate the scenario-specific and daily cumulative risks of infection. In doing so, we have also been able to elucidate the variable impact of infection control interventions across these individual, realistic, and context-driven environmental scenarios, which can be utilized by food industry managers to apply targeted, personalized, and data-informed interventions that would best protect their workforce from infection in their specific occupational context. Furthermore, the framework of our model not only allows for the estimation of infection risk across a variety of additional indoor (e.g., schools, hospitals, restaurants) and outdoor (e.g., open-air markets, recreational venues) environmental scenarios but also establishes a foundational modeling structure that could be adjusted for novel SARS-CoV-2 strains (e.g., increased salivary titers, lower infectious dose) or even other future respiratory pathogen outbreaks. While these multiscenario features are not commonly applied to QMRA models and have been the focus of expansive agent-based modeling work (70), this study highlights the capabilities of QMRA modeling to extend beyond one-time scenario interactions between an infectious and susceptible individual to assess interactions across multiple scenarios.

As for potential limitations, the first would be our assumption of a uniform distribution of viral concentration across all respiratory particle size classes. While this assumption has been implemented by the aerosol modeling work of Zhang et al. (73), it is probably not entirely representative of what is happening in real-world situations. This could have led to an artificially increased risk associated with close proximity ($\leq$1 m) exposure to droplets, given their large diameters (100 to 750 μm) and, by assumption, a higher concentration of infectious SARS-CoV-2 virus. A second limitation is that our model uses the dose-response relationship of SARS-CoV-1 to assess infection risk. Given that the SARS-CoV-2 dose-response parameter(s) have yet to be defined in the literature, this approach has become common practice across multiple SARS-CoV-2 QMRA studies (73–76). We took a multipronged approach to address this limitation, first by generating an approximate SARS-CoV-2 dose-response parameter that translated to an 50% infective dose (ID_{50}) of 102 viral particles, which is within the 10 to 1,000 viral particle range for similar respiratory pathogens (77, 78). Next, we calibrated the viral shedding parameter by using clinical data collected from patients during the first week of symptom onset and a 1:100 conversion factor from PCR-based genome equivalent copies to PFU (79–82), resulting in viral titers of 6.1 to 7.4 $\log_{10}$ PFU. Finally, we calculated the average indoor risk of infection after a 1-h exposure at 1 m to be 0.678 (95% UI, 0.270, 0.984), which is within the attack rate range of well documented SARS-CoV-2 outbreaks in meat processing (attack rate [AR], 30.2%) (8), households (AR, 52.7%) (83), recreational spaces (AR, 53.3 to 86.8%) (84), and food preparation facilities (AR, 60.0%) (85). Taken together, our approach ensures that we are providing risk estimates in realistic, context-specific scenarios that are within the range of documented SARS-CoV-2 outbreaks, while not underestimating the potential infection risk. Another limitation is that we assumed discordant vaccination status (e.g., only the susceptible worker had received a vaccination) among the infected and susceptible produce workers modeled. While vaccine hesitancy has been well documented among the food worker population (86, 87), these findings suggest that daily infection risk can be reduced by promoting a single-dose (73%) or two-dose vaccine (93%). This is of particular importance for the outdoor agricultural worker community, as the transient nature of this worker population highlights the need for public health efforts to continue promoting and advocating for vaccinations in these communities that can reduce infection risk, regardless of occupational setting. Future work is needed to understand the SARS-CoV-2 vaccination coverage levels within this essential worker community, the findings of which could then be incorporated into the present model to increase the generalizability of our results. Lastly, quantitative microbial risk assessment models are not able to easily incorporate the diverse characteristics of groups of susceptible individuals that could lead to a heightened baseline risk of infection (i.e., age or comorbidities such as hypertension, obesity, or diabetes mellitus [88]) or convey the severity and outcome of the infection (i.e., mild asymptomatic or symptomatic disease, moderate disease requiring hospitalization, or severe disease resulting in death). Future work could address these limitations by integrating QMRA models with compartment-based modeling approaches (e.g., susceptible-exposed-infected-recovered [SEIR]). This integration could evaluate the SARS-CoV-2 interventions, infection disease course, and outcomes at the individual and population levels for susceptible produce workers.

Our model has demonstrated that the elevated daily SARS-CoV-2 infection risk experienced by indoor and outdoor produce workers can be reduced to $\leq 2 \times 10^{-3}$ when vaccinations (optimal vaccine efficacy, 86 to 99%) are combined with recommended infection control strategies. Given their consistency in reducing infection risk for both indoor and outdoor produce workers (92.4 to 93.0% reduction), vaccinations should continue to be prioritized as an effective means by which to maintain a healthy workforce and reliable global food supply. However, our findings show that vaccinations alone are not sufficient to bring the cumulative daily infection risk below a 0.01 threshold for either indoor or outdoor worker populations. This underscores the need for vaccinations to be combined with additional infection control interventions (e.g., handwashing, surface disinfection, universal masking, physical distancing, and increased ventilation) implemented by the food industry to further reduce the potential for SARS-CoV-2 transmission. These findings provide additional evidence supporting international (European Union OSHA, WHO), domestic (CDC, U.S. OSHA), and industry-specific (FDA, American Frozen Food Institute [AFFI]) recommendations for preventing SARS-CoV-2 transmission during food production and processing shifts and across various day-to-day exposure scenarios (e.g., shared transportation, employer-provided housing, etc.) (21, 27, 66, 89–96). Taken together, these results highlight the need for produce industry management to continue promoting vaccine uptake in their workforce and support the use of industry-recommended infection control strategies when managing SARS-CoV-2 transmission among essential workers.

MATERIALS AND METHODS

Model overview. The model outcomes include (i) the scenario-specific and the daily cumulative SARS-CoV-2 infection risk for a susceptible produce worker quantified across three viral transmission pathways (aerosol-, droplet-, and fomite-mediated) and (ii) the individual and combined impact of recommended infection control strategies on reducing the daily cumulative risk of SARS-CoV-2 infection for a susceptible produce worker. Leveraging calculations described in our previous SARS-CoV-2 QMRA model (42), we quantified the risk of infection across three transmission pathways (aerosols, droplets, and fomites) for the environmental scenarios pertinent to both indoor and outdoor food workers (e.g., shared transportation, work shift, work break, private/shared housing). Each scenario assumed a single infected symptomatic worker either coughed or breathed virus-laden respiratory aerosols (defined here

TABLE 3 QMRA parameters for SARS-CoV-2 viral transmission[a]

Parameter	Units	Description	Input values[b]	Distribution	References
$Log_{10}(C_{virus})$	$PFU \cdot mL^{-1}$	Concn of virus in saliva	6.80 (6.10, 7.40)	Triangular	79, 103
F_C	$Cough \cdot h^{-1}$	Coughing rate per hour	24.7 (10.0, 39.3)	Uniform	104
$Hand_{sa}$	m^2	Surface area of two palms	1.8×10^{-2} (1.5×10^{-2}, 2.2×10^{-2})	Triangular	105, 106
λ_{hand}	min^{-1}	Viral decay on hand surface	1.20 (0.92, 1.47)	Uniform	107
Freq.hs	$Contact \cdot min^{-1}$	Contact frequency between hands and fomite	8.4 (5.4, 11.4)	Triangular	108
Freq.hf	$Contact \cdot min^{-1}$	Contact frequency between hands and face	0.261 (0.072, 0.450)	Triangular	109
F_{23}	Proportion	Proportion of virus transferred from hand to face	0.200 (0.063)	Normal	110
L_{dep}	Proportion	Deposition fraction of virus into the lungs	1.00	Point	Assumed
I_R	$m^3 \cdot h^{-1}$	Inhalation rate per hour	2.40 (1.62, 3.18)	Uniform	111
k_{risk}[c]	PFU^{-1}	Dose-response parameter to determine infection risk at a given viral dose	6.80×10^{-3}	Point	80

[a]QMRA, quantitative microbial risk assessment; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.
[b]The values presented as mode (minimum, maximum) for triangular distributions, mean (minimum, maximum) for uniform distributions, and mean (SD) for normal distributions.
[c]This upper estimate, within the published k_{risk} range (80), was used to calibrate our model to documented SARS-CoV-2 outbreaks, as described in the materials and methods.

as particles with a diameter $<$50 μm) and droplets (particle diameter 50 to 750 μm) that could infect a susceptible worker. We did not model an infected asymptomatic worker because of their low risk to a susceptible worker, due to low emission of viral particles from breathing (42). Briefly, the aerosol transmission pathway assumed a well mixed environment in which all virally contaminated aerosols would be homogenously distributed throughout the volume of the modeled scenario and would accumulate in the environment over time (73, 97, 98). The aerosols could be removed from the scenario by the scenario-specific air exchange rate or through the relative humidity- and temperature-specific viral decay rate. The droplet-mediated transmission pathway assumed that the virally contaminated droplets would be emitted from the infected worker's cough and reach distances of 1 to 3 m based on their size and would not accumulate in the air over time (99–101). Finally, the fomite-mediated transmission pathway assumed that contamination would occur through the fallout of both aerosols and droplets onto the fomite surface based on the particle's settling velocity and gravitational trajectory (102). These particles could be removed from the fomite through either the surface-specific viral decay rate or by surface disinfection. For each modeled scenario, the susceptible worker's viral dose was combined across the aerosol-, droplet-, and fomite-mediated transmission pathways to obtain a cumulative, scenario-specific viral dose. These environmental scenarios were linked for either an indoor or an outdoor worker, and indoor and outdoor workers had a different set of linked environmental scenarios as described below. All models were constructed in R (version 4.0.3; R Development Core Team; Vienna, Austria) using 10,000 Monte Carlo iterations of literature-derived parameters and their probability distributions, to provide daily cumulative infection risks for each type of worker. Details regarding the QMRA modeling parameters are summarized in Table 3 (79, 80, 103–111). Additional model parameters used to inform the SARS-CoV-2 viral transmission pathways are summarized in Table S1 and grouped into three categories: (i) viral shedding through coughing respiratory events, (ii) fomite-mediated transmission and dose-response parameters, and (iii) risk mitigation interventions (infection control interventions and vaccinations).

Sequential environmental scenarios for indoor and outdoor produce workers. The daily cumulative infection risk was estimated for a susceptible produce worker exposed to a symptomatic SARS-CoV-2-infected co-worker throughout all representative daily environmental scenarios. Susceptibility was defined herein as an individual with no pre-existing health conditions, prior vaccinations, or infections altering their level of susceptibility. Additionally, the infection risk estimates reported for the susceptible worker represents any form of infection (e.g., asymptomatic, mild symptoms, severe symptoms) or timing of illness. These daily environmental scenarios were identified through discussions with industry trade associations, including the AFFI and the Produce Marketing Association (PMA); research and extension experience provided by representatives of the Arizona Cooperative Extension Organization, the Western Regional Center to Enhance Food Safety, and the Emory Farmworker project; and our past research on farms and packing facilities along the United States and Mexico border (112–114). Each scenario (Fig. 1) was modeled as an independent QMRA and expanded from our previous modeling work of SARS-CoV-2 transmission in an indoor food manufacturing facility (42). The SARS-CoV-2 exposure dose was combined across each environmental scenario experienced by the susceptible produce worker to estimate the daily infection risk. Scenario-specific parameters, such as the volume of space modeled, temperature and relative humidity, baseline air exchange rate (ACH), and fomite-specific viral decay, can be found in Table 4.

SARS-CoV-2 dose characterization. The daily cumulative risk of SARS-CoV-2 infection to a susceptible produce worker was calculated by summing the viral dose across each environmental scenario designated to either an indoor or outdoor produce worker. The scenario-specific risk of SARS-CoV-2 infection was calculated by summing the viral dose across each transmission pathway (aerosol, droplet, fomite) for each environmental scenario (shared transportation, work shift, work break, shared housing). Both the scenario-specific and daily cumulative viral doses from aerosol-, droplet-, and fomite-mediated transmission were then converted into risk estimates, as described below.

A susceptible worker may be exposed to aerosol (D_{aero}) and droplet (D_{drop}) viral doses. Aerosol (D_{aero}) and droplet (D_{drop}) doses were both calculated from the concentration of virus in the scenario (C_t) at time t for the specified transmission pathway (aerosol [aero], droplet [drop]), the deposition fraction of particles into the lung

TABLE 4 Environmental scenario-specific QMRA model parameters[a]

	Shared transportation		Occupational location			Residential
Parameter	Car	Bus	Indoor facility	Indoor breakroom	Outdoor field	Shared housing
Total exposure time (h)	2.00	3.00	11.0	1.00	11.0	10.0
Room vol (m^3)	2.60	81.4	460	139	17.0	34.0
Temp	75.0°F (23.9°C)	75.0°F (23.9°C)	65.0°F (18.3°C)	65.0°F (18.3°C)	85.0°F (29.4°C)	75.0°F (23.9°C)
Relative humidity	Low (≤30%)	Low (≤30%)	Low (≤30%)	Low (≤30%)	High (≥50%)	High (≥50%)
Kinematic viscosity (m^2/s)	1.54×10^{-5}	1.54×10^{-5}	1.49×10^{-5}	1.49×10^{-5}	1.59×10^{-5}	1.54×10^{-5}
Dynamic viscosity (Ns^2s/m^2)	1.83×10^{-5}	1.83×10^{-5}	1.80×10^{-5}	1.80×10^{-5}	1.86×10^{-5}	1.83×10^{-5}
Air viral decay (h^{-1})[b] (129)	0.478 (0.150, 0.806)	0.478 (0.150, 0.806)	0.114 (0.048, 0.180)	0.114 (0.048, 0.180)	11.8 (11.1, 12.5)	2.79 (2.13, 3.45)
Baseline ACH (exchange/h)[c]	2.55 (0.98 to 4.10) (122)	11.1 (8.96 to 13.4) (123)	0.10[d]	0.10[d]	991 (584 to 1,298) (130)	0.35[d] (131)
Increased ACH (exchange/h)[c]	29.1 (6.50 to 51.7) (122)	21.6 (10.5 to 37.3) (123)	6.0[d]	6.0[d]	NA	3.90 (2.08 to 5.72) (131)
Fomite material	Polyester	Plastic	Stainless steel	Stainless steel	Stainless steel	Glass
Fomite viral decay (h^{-1}) (132, 133)[e]	0.222 (0.177, 0.267)	0.148 (0.134, 0.162)	0.293 (0.164, 0.422)	0.293 (0.164, 0.422)	0.293 (0.164, 0.422)	0.179 (0.147, 0.211)
Fomite transfer efficacy (134)[c]	0.003 (0.001 to 0.007)	0.217 (0.001 to 0.511)	0.076 (0.017 to 0.139)	0.076 (0.017 to 0.139)	0.374 (0.056 to 0.688)	0.673 (0.176 to 0.839)

[a]The references are used to inform parameter estimates. ACH, air exchange rate; QMRA, quantitative microbial risk assessment.
[b]The uniform distribution values are presented as mean (minimum, maximum).
[c]The values represent mean (95% uncertainty interval).
[d]Point distribution with no standard deviation.
[e]The triangular distribution values are presented as mean (minimum, maximum).

mucosa (L_{dep}), the inhalation rate (I_R), and the duration of exposure (E_t). The sum of aerosol (D_{aero}) and droplet (D_{drop}) is defined as D_{air}.

$$D_{\text{aero}}(t) = C_{t,\text{aero}} \times L_{\text{dep}} \times I_R \cdot E_t$$

$$D_{\text{drop}}(t) = C_{t,\text{drop}} \times L_{\text{dep}} \times I_R \times E_t$$

$$D_{\text{air}}(t) = D_{\text{aero}}(t) + D_{\text{drop}}(t)$$

The fomite-mediated (D_{hand}) viral dose was calculated by using the frequency of hand-to-face contacts (H_{face}), the ratio of finger (F_{sa})-to-hand (H_{sa}) surface area, the concentration of virus on the hand at time t (C_{hand}) for both aerosol and droplet exposure pathways, the fraction of pathogens transferred from the hand to the facial mucosal membrane (F_{23}), and the exposure duration in hours (t) as follows:

$$D_{\text{hand}}(t) = \frac{H_{\text{face}} \times F_{\text{sa}} \times C_{\text{hand}}(t) \times F_{23} \times t}{H_{\text{sa}}}$$

The scenario-specific viral dose was calculated by combining the viral dose for the aerosol and droplet pathways (D_{air}) with the fomite-mediated pathway (D_{hand}) for a specified environmental scenario. For instance, the scenario-specific viral dose for the 11-h indoor processing facility shift ($D_{processing}$) was calculated by:

$$D_{\text{processing}}(t) = D_{\text{air, processing}}(t) + D_{\text{hand, processing}}(t)$$

Finally, the daily cumulative viral dose for an indoor (D_{Indoor}) or an outdoor ($D_{Outdoor}$) produce worker was calculated by combining the scenario-specific viral dosages relevant to each worker as follows:

$$D_{\text{Indoor}} = D_{\text{processing}} + D_{\text{indoor breakroom}} + D_{\text{car transportation}}$$

$$D_{\text{Outdoor}} = D_{\text{field}} + D_{\text{bus breakroom}} + D_{\text{bus transportation}} + D_{\text{housing}}$$

SARS-CoV-2 transmission model calibration and risk characterization. To calculate the probability of SARS-CoV-2 infection for a susceptible worker at a given viral dose, we calibrated our SARS-CoV-2 transmission model as follows. First, we modeled the SARS-CoV-2 viral shedding parameter after peak viral titers in saliva by converting PCR-based genome equivalent copies reported within the first week of symptom onset (4.3 to 7.4 $\log_{10}$ viral copies per mL) to PFU using a 1:100 conversion (6.1 to 7.4 $\log_{10}$ PFU) (79–82). Second, we calibrated the SARS-CoV-2 dose-response parameter to a median infectious dose (ID_{50}) of 102 viral particles (within the documented ID_{50} range of 10 to 1,000 viral particles for similar respiratory pathogens) by leveraging the upper 99.5% bound estimate from 10,000 iterations of the SARS-CoV-1 dose-response parameter (6.80×10^{-3}; Table 3), as previously described by Sobolik et al. (42, 77, 78, 80). To validate these calibrated risk estimates, we calculated the average indoor risk of infection after a 1-h exposure at 1 m to be 0.678 (95% UI, 0.270, 0.984), which fell within the AR range of well documented SARS-CoV-2 outbreaks in meat processing facilities (AR, 30.2%) (8), households (AR, 52.7%) (83), recreational spaces (AR, 53.3 to 86.8%) (84), and food preparation facilities (AR, 60.0%) (85). It should be noted that in a recent human challenge study, which used a single dose of wild-type SARS-CoV-2, the ID_{50} was estimated to be 10 viral particles (115). Although we cannot establish a dose-response relationship based on a single inoculation dose, this ID_{50} estimate (which approximates to 7 PFU) (116) does align with the range of inoculation values (5 to 12,000 PFU) used to establish the dose-response relationship for SARS-CoV-1. Thus, given that our calibrated model aligns with the documented outbreaks described above, we will continue to utilize the ID_{50} of 102 viral particles in our calculations. With our validated model, we then calculated the scenario-specific infection risk (e.g., $R_{car\ transportation}$) and the daily cumulative infection risk (e.g., R_{Indoor}) as follows:

$$R_{\text{car transportation}} = 1 - \exp\left[-k_{\text{risk}} \times D_{\text{car transportation}}\right]$$

$$R_{\text{Indoor}} = 1 - \exp[-k_{\text{risk}} \times D_{\text{Indoor}}]$$

The results are presented as the median risk values with the 95% UI, which is comprised of the 2.5 and 97.5 percentiles. Additionally, the daily cumulative risk estimates are stratified by the distance between the infected and susceptible worker during their 11-h work shift. For example, the daily cumulative risk reported for an indoor worker at 1 m utilizes the dose calculated for the 11-h indoor work shift in which the infected and susceptible workers are separated by a 1-m distance, whereas the daily cumulative risk at 2 m utilizes the dose from the 11-h work shift with the workers separated by a 2-m distance. Given that increased distancing was not applied to other individual scenarios (e.g., transportation, housing, etc.), these did not affect the daily cumulative risk estimates stratified by distance.

Selection of infection control strategies for SARS-CoV-2. Recommended infection control strategies, such as physical distancing from 1 m (3 feet) to 2 m (6 feet), surface disinfection and handwashing during work shifts, masking for both infected and susceptible worker (i.e., universal masking), increased air exchange rates, and vaccination were all identified from a systematic review, conducted by one of the co-authors, of 1,847 United Nations and English-speaking government websites to distill global

TABLE 5 QMRA parameters for risk mitigation intervention efficacies[a]

Parameter	Units	Description	Input values[b]	Distribution	References
HW_{eff}	Log reduction	Hand washing efficacy	0.552 (0.0, 2.0)	Triangular	135
SC_{eff}	Log reduction	Surface disinfection efficacy	0.95 (0.90, 0.999)	Uniform	121, 135
$C_{mask(R)}$	% Reduction	Recipient cloth mask efficacy	52.9 (17.0, 88.7)	Uniform	58, 59, 136
$S_{mask(R)}$	% Reduction	Recipient surgical mask efficacy	68.0 (37.0, 99.8)	Uniform	58, 59, 136
$D_{mask(R)}$	% Reduction	Recipient double mask efficacy	68.5 (40.0, 96.8)	Uniform	58, 59, 136
V_{Opt}	% Reduction	Optimal SARS-CoV-2 vaccine efficacy	92.3 (86.0, 99.0)	Uniform	32, 137
V_{Sub}	% Reduction	Suboptimal SARS-CoV-2 vaccine efficacy	72.0 (64.0, 80.0)	Uniform	33, 138, 139

[a]QMRA, quantitative microbial risk assessment.
[b]The values are presented as mean (minimum, maximum) for uniform and triangular distributions.

guidelines or recommendations to prevent food workers from acquiring COVID-19 (117). These strategies were then vetted with our trade association partners (AFFI, PMA) and extension co-authors (J.K. and C.M.R.) to ensure their alignment and efficacy with the interventions assessed in our models. The impact of these interventions (individually or combined) was evaluated based on the percentage of reduction in infection risk relative to the baseline scenario with no interventions.

Increasing the distance (physical distancing) between workers from 1 to 2 m, based on U.S. Centers for Disease Control and Prevention (CDC) and U.S. OSHA guidance (118), was analyzed in the indoor packing facility and outdoor harvesting field scenarios. It should be noted that in regard to physical distancing recommendations, the World Health Organization (WHO) maintains a 1-m distancing recommendation (119), highlighting the inherent variability in global public health guidance throughout the pandemic. Within these work shift scenarios, the impact of hourly handwashing (2-$\log_{10}$ viral removal) (120) and surface disinfection twice per shift (3-$\log_{10}$ viral removal) (121) was also assessed. The efficacy of various facemask materials (cloth, surgical) and double masking (surgical mask followed by cloth mask) was assessed across all scenarios except for the indoor and outdoor 1-h breaks to allow for eating and in the 8 h in the shared residential scenario to allow for sleeping. The range in efficacy for each facemask material can be found in Table 5 and Table S1.

Scenario-specific increases in air exchange rate (ACH) based on particulate exposure studies were assessed across each environmental scenario except for the 11-h outdoor harvesting field shift and 1-h bus break scenario, given the inability to adjust outdoor ventilation rates. For the shared car transportation scenario, the baseline ACH of 2.55 h^{-1} (95% UI, 0.98 to 4.10) was increased to 29.1 h^{-1} (95% UI, 7.67 to 50.6), which was representative of a 2005 Ford Taurus midsize car traveling from 0 to 50 mph with all windows open to simulate a method for increasing the ventilation rate inside the vehicle (122). For both the indoor packaging facility and associated breakroom, the ACH was increased from 0.1 h^{-1}, representing a facility with negligible ventilation, to 6.0 h^{-1}, representing the facilities surveyed through our conversations with food industry managers across the United States (data not shown). For the shared bus transportation scenario, the baseline ACH of 11.1 h^{-1} (95% UI, 8.96 to 13.4) was increased to 21.6 h^{-1} (95% UI, 10.5 to 37.3), which was representative of a school bus driving under realistic conditions with all windows open to simulate a method for increasing the ventilation rate inside the vehicle (123). For the shared residential scenario, the baseline ACH of 0.35 h^{-1} (point estimate) was increased to 3.9 h^{-1} (95% UI, 2.08 to 5.72), which is representative of opening a window to increase natural ventilation in an apartment-style scenario (124). Additional information on the risk mitigation intervention parameters can be found in Table 5.

Finally, we evaluated the impact of two vaccination scenarios (suboptimal and optimal vaccine efficacies) on reducing the daily cumulative risk of SARS-CoV-2 infection for a susceptible worker. For the suboptimal vaccine (V_{Sub}), the mean vaccine efficacy was 72.0% (95% UI, 64.4 to 79.6%) and represented either receiving one dose of the Johnson & Johnson vaccine, one of the two-dose vaccine series, a reduced vaccine efficacy to novel variants, or incomplete immunity due to a prior SARS-CoV-2 infection (31, 32, 125). For the optimal vaccine (V_{Opt}), the mean vaccine efficacy was 92.3% (95% UI, 86.3 to 98.7%) and represented two doses ($\geq$14 days after final vaccination) of Pfizer-BioNTech or Moderna-NIAD mRNA series vaccines received by the susceptible worker (33, 34). We assumed that only the susceptible worker would be vaccinated across all scenarios and that the vaccine efficacy parameters in Table 5 would represent the susceptible worker's level of immunity to infection. For example, assuming that the indoor susceptible worker was vaccinated with the optimal efficacy vaccine (V_{Opt}), the daily cumulative risk of infection for the optimal vaccine efficacy scenario is represented as:

$$R_{\text{Indoor, Opt.vaccine}} = \left\{1 - \exp\left[-k_{\text{risk}} \times D_{\text{Indoor}}\right]\right\} \times \left\{1 - V_{\text{Opt}}\right\}$$

Although the impact of booster vaccinations or waning immunity to infection was not specifically assessed in the modeled scenarios, these factors are captured by proxy due to the vaccine efficacy ranges against infection assessed in our calculations. For example, receiving three doses of the Pfizer-BioNTech BNT162b2 mRNA vaccine was recently shown to provide a vaccine efficacy against infection of 89.1% (95% confidence interval [CI], 87.5 to 90.5%) (126), which falls within the range of the optimal vaccine efficacy scenario assessed in our models. Furthermore, a recent meta-analysis found that 4 months after receiving the two-dose mRNA vaccine regimen, vaccine efficacy against infection decreased to 62% (95% CI, 53.0 to 69.0%) (127), which falls within the range of the suboptimal vaccine efficacy scenario assessed in our models.

Sensitivity analysis. Sensitivity analyses were conducted for each modeled scenario to determine the most influential parameters in estimating the SARS-CoV-2 viral exposure dose. Parameters identified as being most influential in the final cumulative dose estimate were reported as Spearman rank correlational coefficients using the "tornado" function in the mc2d R package (128). To investigate the propagation of variability and uncertainty throughout the models, the "mcratio" function was used to calculate the variability and overall uncertainty ratio for each modeled parameter. Model stability was achieved after 10,000 Monte Carlo iterations, which was applied across all modeled scenarios (Fig. S1).

Data availability. The code developed and utilized throughout this analysis is available through GitHub at the following DOI: https://doi.org/10.5281/zenodo.8003697.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, DOCX file, 1.1 MB.

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