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By

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Master of Science in Public Health

Environmental Health & Epidemiology

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Abstract

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Essential food and agricultural workers in the United States experience an elevated risk of SARS-CoV-2 infection and mortality due to potential occupational exposures during produce harvesting or packaging. Furthermore, seasonal and migrant farmworker populations commonly rely on employer-provided shared lodging facilities and carpooling behaviors to arrive at their place of employment. The purpose of this study was to quantify the daily risk of SARS-CoV-2 infection for essential food workers from exposures throughout four relevant scenarios (shared transportation, shared lodging, outdoor harvesting field, indoor packaging facility). Additionally, the impact of CDC COVID-19 guidelines (face mask utilization, physical distancing) and existing FSMA requirements (handwashing, glove utilization, surface disinfection) as risk reduction strategies were also assessed. A quantitative microbial risk assessment (QMRA) model was created in R using a two-dimensional Monte Carlo package and 10,000 simulations. Aerosol, close-contact droplet, and fomite-mediated SARS-CoV-2 transmission pathways were examined based on the size distribution of droplets containing infectious SARS-CoV-2 released from an infected index case while coughing and the distance between an infected and susceptible worker (1, 2, or >3m). Without any mitigation strategies, the risk associated with each scenario included: 1h shared transportation (55.1%), 10h residential lodging (90.2%), 12h indoor packing facility shift (12.9%), and a 12h outdoor harvesting shift (14.9%). Relative to no intervention, mask use reduced infection risk by 69.2-82.7% (cloth), 78.5-88.8% (surgical), or 99.5-99.8% (N95) across all scenarios. Furthermore, surface disinfection reduced fomite-mediated transmission when applied daily (4.2%), bi-hourly (89.4%), or hourly (99.9%) in the indoor facility. Overall, these findings highlight the variable risk of SARS-CoV-2 infection across each scenario, with the residential and transportation scenarios resulting in the greatest risk of potential infection, while occupational risks are comparably lower. Across all scenarios, fomite-mediated infection risk remained negligible. These results highlight the potential risks associated with common practices in the agricultural sector (shared lodging, carpooling behaviors) while emphasizing the effectiveness of face mask and physical distancing interventions. Industry stakeholders can leverage these findings during policy creation (limiting shared contact between workers) and targeted risk reduction analyses (focusing on high-risk scenarios), to create a safer living and working environment for essential food workers.

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TABLE OF CONTENTS

1. Literature Review

Globally, the cumulative number of SARS-CoV-2 cases has risen steadily since December of 2019 where the first cases of a novel human pneumonia infection were reported in the city of Wuhan, China[1]. In the United States alone there have been 30.3 million cases of SARS-CoV-2 infection, with over 550,000 attributable deaths as of March 30, 2021[2]. Over a year prior, the World Health Organization (WHO) declared the virus a global pandemic, leading many national and international governances to issue shelter-in-place mandates for their citizens[3]. In response to these mandates, which asked citizens to only leave their homes for food or medication resupplying and outdoor exercising, many business responded by shifting their workforce to remote locations[4]. These governmental mandates and teleworking shifts were not applicable to all workers, as many occupations require a physical presence to perform their duties. Consequently, these workers experienced a higher risk of contracting SARS-CoV-2 while engaging in job-related activities, thus affording more opportunities for the virus to continue spreading throughout these communities. The present literature review seeks to foreground the factors coalescing into an increased infection risk by highlighting food and agricultural workers. In so doing, I will explore the theoretical transmission routes of SARS-CoV-2 that are of particular relevance for this worker population. Finally, I will overview the present and future applications of quantitative microbial risk assessment (QMRA) models in terms of SARS-CoV-2 transmission, infection mitigation strategies, and how this methodology can be applied to food and agricultural worker populations.

1.1 Characterization of Essential Workers

The term, "essential worker" has become commonplace in the vernacular of United States residents; however, a legal definition for the phrase prescribed by the U.S. Congress was lacking until recently[5]. In fact, there are only two entries of "essential worker" in the Oxford English Dictionary prior to 2020[6]. The first refers specifically to teachers in the mid-19th century; nearly 100 years later, it's used again to define migrant workers who qualify for passage under Australian law. The term found new life, however, in the legal, medical, and political discourse surrounding the pandemic. On May 15th, 2020 the U.S. House of Representatives passed the Health and Economic Recovery Omnibus Emergency Solutions (HEROES) Act[7]. Within this act, "essential workers" are defined as: health sector employees, emergency response workers, sanitation workers, and other employees that cannot telework. Furthermore, the definition provides "State and local governmental officials" the power to determine which businesses must remain open during the pandemic, leaving the employees of which to also be considered "essential workers".

While this act provides State and governmental officials with the autonomy to define essential workers as they seem fit, the varying inclusion and exclusion criteria for workers to be deemed "essential" may exacerbate prevalent health inequities. For example, prior to this congressional definition for "essential workers", the National Conference of State Legislatures (NCSL) stated that of 43 states with "essential worker directives", 21 defer to the U.S. Cybersecurity and Infrastructure Security Agency (CISA) definition, while the remaining 23 states have developed their own meaning for the term[8]. The lack of a shared definition for this group of workers among all local and State governances leaves room for vague and variable interpretations of who qualifies as an essential worker. Consequentially, workers in equivalent positions within the same state could be differentially prioritized for the distribution of personal protective equipment (PPE) and more recently, SARS-CoV-2 vaccinations. A recent letter was sent in December of 2020 from the Washington State Supreme Court to the governor in order to clarify a lack of consistency in the State's definition of "essential workers"[9]. Within the letter it is mentioned that the employees of the Washington Court are considered "essential workers" in the State's original SARS-CoV-2 Response Plan; however, they were not considered essential in the subsequent vaccination distribution plan. This exemplifies a lack of consistency among definitions used within the same state, further emphasizing the need for a formal and uniform definition to ensure equitable access across and within state borders.

For the purposes of this thesis project, the term "essential worker" will be used to describe any worker that must physically report to their place of employment to complete their work throughout a public health emergency, such as the coronavirus pandemic. The term "frontline worker" has gained similar colloquial usage as of late; however, the term has historically been used to describe "an employee who provides a service regarded as vital within the community, such as a health-care worker, teacher, et cetera"[6]. In 2019, McNicholas and Poydock[10] reported that of the roughly 55 million essential workers in the U.S., 70.2% were not employed as health-care workers. Although the heroic efforts of health-care workers should not go unpraised, the 70.2% of essential workers employed in other industries should not go unrecognized.

Often overrepresented in essential worker occupations, communities of color have been characterized as having a disproportionately higher rate of SARS-CoV-2 related mortality and other health-related inequities when compared to non-essential workers[11]. With 70% of essential workers lacking a college degree[10] and one-third being classified as economically vulnerable based on income[12], the SARS-CoV-2 pandemic has had a disproportionate impact on these worker populations. In the food and agricultural sector alone, McNicholas and Poydock[10] have reported that over half of these essential workers are from communities of color. Within the food and agricultural sector, numerous SARS-CoV-2 outbreaks have been reported in meatpacking industries[13,14], produce processing facilities[15], and agricultural farms[16–18]. Since April of 2020, the Food & Environment Reporting Network (FERN) has been tracking outbreaks of SARS-CoV-2 infection in these agricultural industries. There have been 1,833 meatpacking (31.2%), produce processing (46.6%), and farm facilities (22.2%) that have reported confirmed cases of SARS-CoV-2 infection, with an overall case count of at least 89,051 and 378 deaths as of April 2, 2021[19]. With over half of food and agricultural workers experiencing a disproportionately higher rate of SARS-CoV-2 mortality based on race alone, we must ensure the health and safety of this keystone population of workers responsible for maintaining the nation's food supply. As such, this thesis project will foreground essential food and agricultural workers to identify potential factors contributing to their increased risk of SARS-CoV-2 infection and mortality.

Food and agricultural workers are often described as working in close proximity of one another on the processing facility assembly line[13] or in the outdoor agricultural fields[17]; however, these workers often spend time in close proximity scenarios outside of work. Steinberg et al.[13] has hypothesized that potential SARS-CoV-2 outbreaks in the meat packaging industry could be attributed to the close proximity of workstations and duration of contact between workers during their work shift. Additionally, Quandt et al.[17] describes that outdoor agricultural workers often work in close proximity while harvesting produce items. Even outside of work, essential food and agricultural workers are expected to spend time together in close-contact scenarios. As documented in Vallejos et al.,[20] among farmworker populations in North Carolina, 95.3% relied on employer-provided shared housing. The conditions of employer-provided housing have been heavily critiqued in the literature, with commonly reported issues surrounding crowded housing[21–24], poor ventilation[23–25], and structural integrity[20,22,23]. Similarly, Reid et al.[26] reported that out of 8,698 farmworkers, roughly 31.4% engaged in shared modes of transportation (carpooling, work bus) to commute to their place of employment. Not only are these essential food and agricultural workers expected to continue working throughout the pandemic, but they are also expected to share living and transportation spaces to perform their job. Given that shared living facilities[27,28] and transportation methods[29,30] have been implicated in many SARS-CoV-2 outbreaks outside of this worker population, it is likely that food and agricultural workers are at a heightened infection risk as a result of these shared spaces.

1.2 Transmission Routes of SARS-CoV-2

In a recent systematic review, Sheleme *et al.*[31] characterized the clinical presentation of SARS-CoV-2 infection, highlighting fever, cough, fatigue, dyspnea, and sputum production as the chief clinical symptoms. This is consistent with previously characterized clinical presentations of related members of the *Coronaviridae* family, such as Middle Eastern Respiratory Syndrome[32] (MERS) and the original SARS-CoV[33]. Traditionally, it is believed that the routes of transmission for respiratory pathogens involve infectious contact between the salivary excretions of an infected individual and the mucus membranes of a susceptible individual[34]. This infectious contact is thought to occur through three distinct transmission routes: physical contact, droplet transmission, and aerosol transmission[35]. Physical contact transmission can occur through the transfer of infectious viral particles from the infected to susceptible individual either through direct contact between individuals, or indirect contact with a contaminated fomite surface. The term "fomite-mediated transmission" will be used herein to describe the indirect transmission route of respiratory pathogens. Droplet transmission occurs through contact between a respiratory droplet containing infectious viral nuclei and a susceptible mucus membrane (oral, ocular, nasal). Finally, aerosol transmission is mediated by the inhalation of small-diameter particles containing infectious viral nuclei into the respiratory system of a susceptible individual.

The size classification of forcefully exhaled salivary excretions remains heavily debated, particularly in regards to differentiating between aerosols and droplets[35]. Historically, these droplets were not classified into two separate categories; rather, all salivary particles released were termed "droplets"[36]. With increased technological capabilities to differentiate between the various size classes of these particles, Papineni and Rosenthal[37] were among the first researchers correlate the term "aerosol" with particles that are capable of remaining suspended in the air and traveling longer distances than larger droplets. More recent guidance from the Centers for Disease Control and Prevention (CDC) used a 5µm particle diameter to differentiate between aerosols (<5µm) and droplets (>5µm)[38]. However, variable differentiations are made in the literature with Zhang et al.[39] using 10µm as the cutpoint, Nicas et al.[40] using 20µm as the cutpoint, and Morawska[41] using 100µm as the cutpoint. Clearly, the size classification system used to differentiate between aerosols and droplets is heavily contested in the literature; therefore, the working definition of an "aerosol" will refer to a particle with a diameter ranging from 2-50µm, with any larger diameter being classified as a "droplet".

Differentiating between the aerosol and droplet size classes is necessary to appreciate the unique trajectories each group of particles utilize when forcefully excreted. This forceful excretion can occur through breathing, coughing, or sneezing; however, because SARS-CoV-2 presents clinically with coughing symptoms, this mode of excretion will be of focus. The size distribution and respective concentration of particles released during a coughing event has been extensively researched[36,37,42–45]. Of similar importance to the size distribution of these particles is the method in which they spread in the environment upon exhalation from an infected individual. Recently, Bourouiba et al.[46] leveraged experimental and fluid dynamic mathematical modeling approaches to describe the mode of transmission for excreted aerosols and droplets. Within this novel study, sneezing and coughing respiratory events were described as producing a multiphase turbulent cloud containing aerosols and droplets of varying size ranges. The humid environmental conditions within the respiratory cloud increase the ability of aerosols and droplets smaller than 100μm to persist for increased durations of time in the air and travel up to 7-8m upon exhalation. Related laboratory studies characterize respiratory droplets as following a semiballistic trajectory upon expulsion that are capable of reaching distances of 1-2m[47].

Regardless of the trajectory that aerosol and droplet particles utilize, both have been implicated in the contamination of fomites; therefore, fomite-mediated transmission of SARS-CoV-2 is feasible. This possibility has been explored in related coronaviruses, such as MERS and SARS-CoV, where hospital environmental sampling studies detected viral residue on high-contact surfaces[48]. The predominant mechanism of viral transfer from fomite surfaces to susceptible mucous membranes has been documented in influenza modeling studies. The risk associated with fomite-mediated infection is dependent on the concentration of virus available on the fomite surface, the frequency of contacts made between a hand and the surface, and the material being used as the fomite object[49]. Community sampling of high-touch fomite surfaces in Belo Horizonte, Brazil[50] and Somerville, Massachusettes[51] have detected SARS-CoV-2 on public transportation terminals, community trash bins, and the doorhandles of businesses. Upon further scrutiny in a recent fomite-specific QMRA model, the concentrations of virus detected in these two community sampling studies yielded a maximum infection risk of 1.60×10^{-4}, indicating that this is not likely to be the predominant transmission pathway attributing to infection risk[52].

Applications of Quantitative Microbial Risk Assessments (QMRA)

The QMRA modeling approach provides a framework for characterizing the risk of infection after exposure to a pathogen found in the environment using a dose-response model[53]. There are four steps to conducting a QMRA: hazard identification, exposure assessment, dose-response, and risk characterization[54]. Hazard identification refers to the characterization of pathogen parameters, such as the viral titer or half-life, along with the environmental context of interest. Using a series of probabilistic models, the exposure assessment is then conducted across thousands of model repetitions to determine the pathogenic concentration a susceptible individual in the modeled context would be exposed to. This pathogenic dose is then incorporated into a pathogen-specific dose-response model, which provides the probability of infection based on the concentration of pathogen in the environment. Finally, across all iterations of the probabilistic and statistical models, the average risk of infection can be quantified based on the pathogen and environmental context being modeled.

Originally achieving popularity in the field of waterborne pathogen infection risks[53], the QMRA modeling approach has been adapted to a number of infectious diseases ranging from Norovirus[55] and *Cryptosporidium*[56], to MERS[32] and more recently SARS-CoV-2[39,57–61]. The environmental context of these QMRA models are equally as variable as the pathogens being modeled. For example, SARS-CoV-2 QMRA models alone have investigated infection risks in outdoor markets[39], multi-unit apartment complexes[58], and wastewater treatment facilities[59–61]. While there are many benefits to utilizing the QMRA modeling approach, such as the ability to determine the effectiveness of surface disinfection[57] and face masks[62] at reducing infection risk, these models are often limited by the availability and uncertainty of pathogen-specific parameters[52]. To address the variability and uncertainty of modeled parameters, sensitivity analyses are conducted to quantify the propagation of uncertainty and correlational relationships between parameters and infection risk throughout the model.

The QMRA framework is particularly beneficial for assessing SARS-CoV-2 risks and mitigation techniques, as data and guidance are rapidly being disseminated throughout the literature. The predominant agency providing risk mitigation guidance in the United States is the CDC, which has been promoting the utilization of facemasks[63], social distancing[64], and hand hygiene practices[65] since the onset of the pandemic. While the guidance provided by the CDC pertain to all members of society, essential food and agricultural workers must also adhere to guidance provided by the Food Safety Modernization Act (FSMA) while working[66]. The FSMA is based on mitigating the transmission of foodborne illnesses at various points throughout the supply chain by outlining hand hygiene, glove use, and surface disinfection protocols for food workers. While previous QMRA studies have investigated the role of handwashing practices on reducing the risk of foodborne illness[67], none have been conducted that investigate the impact of FSMA guidelines on reducing the risk of respiratory infections like SARS-CoV-2.

Purpose and Significance of the Present Study

To date, there have been no QMRA modeling studies investigating the occupational risk associated with many essential industries. The SARS-CoV-2 infection risk associated with the healthcare, transportation, and food and agricultural essential industries remain to be assessed. Furthermore, across the SARS-CoV-2 QMRA modeling studies that have been conducted, the collective risk from all three transmission pathways (aerosol, droplet, and fomite-mediated) has yet to be quantified. These transmission pathways are of particular relevance to food and agricultural workers, as their work involves close proximity to one another either on the processing lines or in the produce fields. Shared transportation and housing facilities are commonplace among many of these workers, further increasing their risk of potential infectious contact even when not at work.

Thus, the objectives of our study were to: 1) quantify the risk of SARS-CoV-2 infection for an essential food worker in four relevant scenarios (shared transportation, shared housing, outdoor harvesting field, indoor packaging facility), 2) characterize the impact of individual and combined intervention implementation on reducing infection risk.

Achieving these objectives will underscore the importance of prioritizing the health and wellbeing of essential food workers, especially as the second SARS-CoV-2 afflicted agricultural season approaches in the summer of 2021. Our modeling approach will identify the scenarios of relevance to an essential food worker that could increase their risk of infection across each SARS-CoV-2 transmission route. With this knowledge, food and agricultural industry stakeholders will be able to leverage our scenario-specific findings to provide targeted risk mitigation guidance for their employees, with the goal of lessening their likelihood of infection. We will also assess the impact of various infection mitigation recommendations and requirements made by the CDC and FSMA, respectively, in the hopes of highlighting their effectiveness at reducing infection risk for essential food worker communities. The collective findings of our model could be used to inform essential food worker-related policy creation directed at reducing their risk of infection across all shared spaces. As the pandemic progresses, the industry and policy applications of our modeled results could be used to lessen the burden of infection experienced by the essential food worker population.

2. Materials and Methods

2.1 Model overview

The conceptualization and design of this model was informed by SARS-CoV-2 QMRA studies simulating infection transmission in both a seafood market[39] and a wastewater treatment facility[60]. These models provided insight into the particle transmission behavior and subsequent aerosolized viral transmission pathways that were explored in our model. Risk assessment studies involving related coronaviruses, namely the Middle East Respiratory Virus[32] (MERS) and SARS-CoV[33,68], were leveraged to inform indirect transmission pathways mediated through environmental reservoirs and the biological decay observed in these settings. The fluid dynamics of respiratory droplets expired in either a coughing or breathing event[40,46] and the distances these particles were able to travel based on their sizes have been informed by respiratory particle transmission models[47] and empirical clinical laboratory analyses[42,69].

2.2 Model structure

The outcomes of the model included: the individual and combined risk of SARS-CoV-2 infection for a susceptible worker in different scenarios (residential, transportation, outdoor field, and indoor packaging facility). Additional outcomes included the cumulative infection risk reduction based on the utilization of facemasks and hand hygiene or surface disinfection practices. To visualize the transmission pathways that were analyzed in the model, a QMRA schematic was constructed in Figure 1. The pathways begin with a single infected worker coughing to produce virus-containing respiratory droplets and aerosols.

The distances these infectious particles are able to travel is based on the diameter of the particle produced. For example, the aerosols with a diameter less than 60μm have been shown to travel over 3m, those ranging from 60-100μm can travel up to 2m, and the droplets greater than 100μm can travel up to 1m. Droplets ranging in diameter less than 60μm were capable of remaining aerosolized in the environmental reservoir, whereas the droplets with diameters greater than 60μm followed a projectile trajectory and rapidly fell out of the air onto the floor or fomite. The concentration of virus in air and on the fomite was modeled in plaque-forming units (PFU) per volume defined by each modeled scenario, or PFU per surface area of the fomite. The infection risk for a susceptible worker was calculated based on each of the transmission pathways described in Figure 1. The first transmission pathway characterized was the close-contact droplet spray, where the susceptible worker was located less than 3m from an infected worker displaying coughing symptoms. The second transmission pathway explored the inhalation of small-diameter aerosols containing infectious viral particles that were capable of remaining suspended in the environmental reservoir. The final pathway investigated the role of viral transmission through tactile events between a susceptible worker's hand and a contaminated fomite, with subsequent viral transfer to the worker's face.

The model is composed of three transmission pathways that were defined in the risk assessment: aerosol transmission of particles with diameters ranging from 0.6-2.2μm (breathing event) or 2-50μm (coughing event); direct close-contact transmission of expired droplets ranging from 0.6-2.2μm (breathing event) or 2.0-750μm (coughing event) in diameter; and indirect transmission mediated by an environmental reservoir contaminated with viral particles based on particle deposition probabilities summed across both aerosol and close-contact pathways[69]. This model was applied to each scenario (harvest field, indoor packing facility, shared transportation, and shared housing) to modulate the typical workday of an essential agricultural worker. Each scenario will be customized with relevant parameters such as dimensions of the space/facility, air exchange rate, and fomite composition, more information can be found in Supplemental Table 1.

Two events were evaluated in the model, the first being an asymptomatic infected worker who generates infectious respiratory particles through breathing, and the second a symptomatic infected worker who generates infectious respiratory particles through coughing. It was assumed that there would be one index infected worker per scenario. The model was developed in R (version 4.0.3; R Development Core Team; Vienna, Austria) and utilized the mc2d package for both Monte Carlo simulations and sensitivity analyses[70].

2.3 Data sources

The parameters were grouped into three categories and can be found in Table 1. These include: (i) viral shedding through breathing and coughing respiratory events, (ii) intervention methods that were assessed (including mask type, surface disinfection frequency and efficacy, hand hygiene frequency, etc.), and (iii) infectious dose parameters for fomite-mediated transmission, respiratory deposition rate, and dose-response parameters to calculate risk of SARS-CoV-2 infection. Viral concentrations in saliva were based on clinical quantifications of SARS-CoV-2 virus[71,72]. The amount of saliva released per coughing or breathing event were based on risk analyses conducted for influenza, with a representative 0.044mL of respiratory fluid emitted per cough[37,40,49]. Respiratory particle counts and size distributions per coughing and breathing event were obtained from previous laboratory-based studies[36,37,40,42,46]. These estimates were used to generate volume fractions per droplet size range, those being <50μm, 50-60μm, 60-100μm, and >100μm. Viral decay rates were based on SARS-CoV-2 viral stability analyses conducted with clinical samples[73,74]. Recent laboratory studies were used to characterize the efficacies of cloth, surgical, sub-optimally fitting N95 and optimally fitting N95 face masks[75–78] which are recommended by the WHO[79] and CDC[63]. The efficacies of surface disinfectants being used encompass those found on the EPA List N: Disinfectants for Coronavirus (COVID-19)[80]. The frequency of handwashing, glove changes, and proportion of virus transferred from contaminated hands to gloves during the gloving process were based on previous findings from norovirus transmission studies in the agricultural setting[81]. The proportion of SARS-CoV-2 transferred from fomite to hand and from hand to face were based on prior studies quantifying the risk associated with indirect transmission of influenza virus[49,82]. Finally, parameters associated with the dose calculation were inhalation rate and lung deposition fractions, which were based on models of pathogenic bioaerosols, and the dose-response parameter represents that of the original SARS-CoV[39,83].

2.4 Aerosol transmission modeling

The following aerosol transport model was leveraged from a SARS-CoV-2 risk assessment model based on a Chinese Seafood Market[39]. The sole source of infectious virus released into the environment was through either a breathing or coughing respiratory event, with total viral shedding being calculated as:

$$E_{virus} = V_F \cdot Freq_E \cdot 10^{(\log_{10} C_{virus})}$$

Where E_{virus} represents total virus shed per hour (PFU/hr), V_F represents the fraction of volume associated with a specific range of droplet sizes (μm) per respiratory event, $Freq_E$ represents the frequency of respiratory event per hour, and C_{virus} represents the concentration of viral particles in the saliva (PFU/mL). Similar to prior risk assessment studies, a single-compartmental model was used to calculate the concentration of SARS-CoV-2 viral particles within the environment using the viral shedding equation above[39]. It was assumed that the aerosolized particles would be homogenously distributed throughout the environment and follow viral decay rates specific to the relative humidity being modeled. In addition to viral decay, it was assumed that viral particles would be lost through deposition onto a surface or through the ventilation relative to the scenario being modeled. The total loss of volume containing virus per second was calculated as:

$$V_{loss} = Q + (\lambda_v \cdot f_V)$$

Where V_{loss} represents the concentration of viral particles lost per second (m^3/s), Q is the ventilation rate (m^3/s), λ_v is the viral decay rate (s^{-1}), and f_V is the facility volume (m^3). The concentration of SARS-CoV-2 particles in the air reservoir were calculated as follows:

$$C_t = \frac{1}{V_{loss}}\left(1 - exp\left(\frac{-V_{loss} \cdot \Delta t}{f_V}\right)\right) \cdot \sigma + C_{t-\Delta t} \cdot exp\left(\frac{-V_{loss} \cdot \Delta t}{f_V}\right)$$

$$C_{t=0} = 0$$

Where C_t is the concentration of virus (PFU/m^3) at time t, (hour) and is equal to 0 at the initial timepoint, σ is the viral shedding rate (PFU/s), Δt is the change in time (s^{-1}) from the prior one-hour time step, and $C_{t-\Delta t}$ is the change in concentration between time steps to account for viral carryover and viral loss. It was assumed that the amount of virus falling out of the air reservoir was equal to the difference between the total virus shed at time t and the subsequent concentration of virus at time t, based on the volume of the facility.

2.5 Close-contact droplet transmission modeling

The close-contact transmission model was based on the viral spray of particles from an infected worker to a susceptible worker that are within 3m of each other. Based on evidence that larger sized droplets follow a ballistic trajectory and fall out of the air at a much faster rate than smaller particles which can remain aerosolized[46,47], we assumed that there would be no carryover of viral particles in the air between the one-hour time steps. As a result of these differing size dynamics, particle probability estimates (denoted *pp*) were used to generate the proportion of droplets that are capable of reaching distances ranging from 0-3m based on the equation below:

$$C_t = \left[\frac{1}{V_{loss}}\left(1 - exp\left(\frac{-V_{loss} \cdot \Delta t}{f_V}\right)\right) \cdot \sigma\right] \cdot pp$$

Where *pp* represents the probability that a particle will reach a pre-specified distance ranging from 0-3m. These probabilities were acquired for both coughing and breathing events based on previous studies investigating the dynamics of expired respiratory particles[43]. The inverse of this probability was used to determine the number of viral particles that fell out of the air and contaminated the fomite surface ($Fall_t$).

2.6 Fomite-mediated transmission modeling

The viral concentration on the fomite was derived from the viral fallout associated with both the aerosol and close-contact transmission pathways. To calculate the concentration of viral particles on the fomite surface at time t, we used:

$$F_t = F_{t-1} + \frac{Fall_t \cdot f_V \cdot H_{sa}}{f_a}$$

$$F_{t=0} = 0$$

Where F_t is the viral concentration (PFU/m^2) on the fomite surface at time t, $Fall_t$ is the proportion of virus available for contaminating the fomite surface (PFU/m^3), f_V is the volume of the facility (m^3), H_{sa} is the surface area of a hand that touches the fomite (m^2), and f_a is the cross-sectional area of the facility being modulated (m^2). Based on prior risk analyses pertaining to fomite-to-hand and hand-to-face transmission of influenza virus, we calculated the concentration of SARS-CoV-2 transferred to a hand following a tactile event at time t as:

$$C_{hand}(t) = \frac{H_{surface} \cdot F_t \cdot F_{12}}{\lambda_{v,hand}} \cdot \left[1 - exp\left(-\lambda_{v,hand} \cdot t\right)\right]$$

Where C_{hand} is the viral concentration on a hand at time t, (PFU/hr), $H_{surface}$ is the frequency of contacts between the hand and fomite per minute (contacts/min), F_t is the viral concentration on the fomite (PFU) at time t, F_{12} is the proportion of virus transferred from fomite to hand based on the defined relative humidity, and $\lambda_{v,hand}$ is the viral decay of SARS-CoV-2 on the hand.

2.7 Modeled scenarios

To assess the individual and cumulative SARS-CoV-2 infection risk to an essential produce worker following exposure throughout their work day, four scenarios were generated: (i) a residential, shared housing scenario representing the on-site housing facilities used by seasonal agricultural workers, (ii) a transportation scenario in which agricultural workers would travel in a shared vehicle twice in a work day to the harvesting field from the shared housing in the morning and returning to the housing facility at the end of the work day, (iii) an outdoor field scenario where agricultural workers harvest fresh produce, and (iv) an indoor packaging facility prior to commercial distribution. We assumed susceptible workers spent 10 hours in the shared housing scenario, 2 hours per day in the transportation scenario, and 12 hours per day in either the outdoor harvesting or indoor packaging scenario per expert elicitation from industry sponsors. Industry experts were tasked with completing a short survey regarding the practices of their food workers, yielding the baseline timeframe for our scenario-specific assumptions. The cumulative risk of SARS-CoV-2 infection across each of these scenarios was calculated using the inclusion and exclusion criteria described in Nicas et al.[49].

2.7.1 Transportation scenario

Outbreaks associated with shared transportation have been well documented[29,30,84–86]. To reflect the shared transportation frequently used in the agricultural setting, model parameters were adjusted to reflect this scenario. Workers were assumed to spend two hours per day in this scenario to account for travel time to and from the shared housing and occupational location. Based on in-vehicle air pollution studies, the volume attributed to the vehicle was $2.6m^3$ and represents that of a 2005 Toyota Corolla with an air exchange rate ranging from $0.92hr^{-1}$ when parked to $2.2hr^{-1}$ upon driving 20mph[87]. The relative humidity was assumed to fall within the low category of 20-40% with a temperature of 75ºF based on similar particulate matter exposure studies[88–90]. Infectious respiratory particles were assumed to accumulate on the polyester interior found within the vehicle, with fomite-to-hand transfer efficacies relative to the porous interior and humidity being modulated using MS-2 as a proxy[91]. Finally, we assumed that the infected and susceptible worker would not engage in face-to-face contact while in transit such that only the accumulation of aerosolized particles in the environmental reservoir would be used to estimate the risk of infection

2.7.2 Residential scenario

Recent outbreaks in residential housing demonstrated the potential for transmission in essential agricultural worker on-site housing facilities[24,92]. For exposure duration in this scenario, we assumed that 10 hours would be spent in the residential scenario per day. The dimensions allocated to the residential area were based on OSHA minimum guidelines of 50ft^2 per occupant per room for employer-provided housing[93]. Air exchange rates in this setting were assumed to meet ASHRAE Standards, with a rate of 0.35 air exchanges per hour[94]. Based on cross-sectional survey data conducted in the summer months, the relative humidity was assumed to fall within the high category of 60-80%[73], and the temperature was assumed to be 75ºF[95].

Within this shared housing scenario, infected and susceptible individuals were assumed to be within 3m of one another for two out of ten hours to account for shared living room, kitchen, and bathroom interactions. Expired respiratory droplets were assumed to accumulate on a glass-surface table ranging in size from 1-4ft^2. The fomite was assumed to be between the infected and susceptible worker, with fomite-to-hand transfer efficacies relative to the table surface material and humidity being modeled using the MS2 bacteriophage as a proxy[91].

2.7.3 Outdoor field harvesting scenario

There have been over 73,000 documented agricultural workers testing positive for SARS-CoV-2, with approximately 15% of these infections attributed to outdoor farmworkers[19]. An outdoor field scenario was generated to model the harvest environment of fresh produce. It was assumed that an infected worker would be positioned on one side of the tractor to harvest the produce items, while the susceptible worker would be on the tractor sorting the harvested produce into containers. The volume of space attributed to this scenario was 128m^3, simulating the volume of space surrounding typical commercial harvesting equipment. We used a uniform distribution of windspeeds ranging from 5-10mph to account for prevailing winds in the outdoor environment. Given that anemometers are traditionally used at 10m heights to measure windspeeds, the log wind profile equation[96] was used to adjust for breathing heights:

$$w_b = w_{ref} \cdot \frac{\ln\left(h_b / z_0\right)}{\ln\left(h_{ref} / z_0\right)}$$

Where w_b is the wind velocity (m/s) calculated at breathing height h_b (m), w_{ref} is the known wind velocity (m/s) at the reference height h_{ref} (m), and z_0 is the roughness length given the agricultural landscape (m). The resulting windspeeds were then used as a proxy for the air exchange rate of Q for this scenario. Given the nature of outdoor produce collection work that is typically done in the mid-to-late summer months, the ambient temperature was assumed to be 90ºF with a relative humidity ranging from 60-80%. For the fomite-mediated transmission pathway, infectious respiratory particles that fell out of the air were assumed to land on the stainless-steel worktable used by workers to process produce prior to packaging. Fomite-to-hand transfer efficacies relative to the steel surface and humidity were incorporated into the model[91]. Exposure time in this scenario for a susceptible outdoor worker was assumed to be twelve hours per day and was informed by communications with food industry experts.

2.7.4 Indoor packing facility scenario

Indoor packing facilities, such as those associated with meat packing or food processing, have attributed 85% of the agricultural workers that have tested positive for SARS-CoV-2[19]. We modeled the area surrounding shared processing tables and conveyer belts, with an assumed volume of 457m^3. The air exchange rate in the facility was assumed to be 2hr^{-1} based on ASHRAE standards[94], with a low relative humidity and temperature of 65ºF. Infectious respiratory particles that fell onto a surface were assumed to accumulate onto a stainless-steel processing area where workers packaged and processed their commodities, with fomite-to-hand transfer efficacies relative to the steel surface and low humidity indoor environment[91]. In this scenario, indoor packaging facility workers were simulated to spend twelve hours per day working.

2.8 Risk assessment

The cumulative risk of SARS-CoV-2 infection for an essential agricultural worker per day was based on the three viral transmission pathways assessed in each of the modulated scenarios for an indoor and outdoor agricultural worker. The first was that for a produce harvester working outside to collect agricultural goods, while the second scenario was for an indoor packaging worker handling meat or produce items. The viral exposure due to the aerosol and droplet pathway was based on the concentration of virus remaining in the air

(C_t), the deposition fraction of particles into the lung mucosa (L_{dep}), the inhalation rate (I_R), and the duration of exposure (E_t). The equation used to estimate the viral dose associated with the air environmental reservoir was:

$$D_{air}(t) = C_t \cdot L_{dep} \cdot I_R \cdot E_t$$

Using an exponential dose-response model (k_{risk}) based off of clinical studies for SARS-CoV, the viral dose for aerosol exposure was converted to a probability of infection for SARS-CoV-2 for a susceptible agricultural worker. The equation used to estimate the risk for the air environmental reservoir was:

$$R_{air}(t) = 1 - \exp\left[-k_{risk} \cdot D_{air}(t)\right]$$

The viral dose a susceptible worker could be exposed to from both the aerosolized particles and larger diameter respiratory droplets that contaminated the fomite was based on the frequency of contacts between the hand and face (H_{face}), the surface area of the hand (H_{sa}), the concentration of virus on the hand at each time t (C_{hand}), the fraction of pathogens transferred from the hand to the facial mucosal membrane (F_{23}), and the exposure duration in hours. The equation used to estimate the dose attributed to the fomite-mediate transmission pathway was:

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

The facial mucosal membrane being modeled was based on influenza risk assessment studies that used the lips, eyes, and mouth of a susceptible individual as the mucosal membrane vulnerable to infection by contact with a contaminated hand. The dose of infectious viral particles contaminating the surface of a hand that makes contact with the oral mucosal membrane was used to estimate the risk of SARS-CoV-2 infection through the fomite-mediated indirect infection pathway. The equations used to estimate the risk associated with fomite-mediated viral transmission was:

$$R_{hand}(t) = 1 - \exp\left[-k_{risk} \cdot D_{hand}(t)\right]$$

The cumulative risk of SARS-CoV-2 infection over a period of twenty-four hours was calculated by summing the dose of viral particles a susceptible worker is exposed to from each of the transmission pathways, as shown below.

$$C_{risk} = R_{air} + R_{fomite} + R_{close-contact} + R_{air} \cdot R_{fomite} \cdot R_{close-contact}$$

It was assumed that each dose had an independent probability of infecting the susceptible worker; thus, similar to previous microbial risk assessments[49], we used an inclusion-exclusion approach to estimate the cumulative risk of infection across each transmission pathway.

2.8.1 Sensitivity Analysis

To reflect the inherent variability in a risk assessment model, a sensitivity analysis was conducted over 10,000 simulations to determine the most influential parameters in estimating the risk of SARS-CoV-2 infection for an essential food worker. The parameters identified as being most influential in the final cumulative risk estimate were reported as Spearman rank correlational coefficients using the "tornado" function in the mc2d R package[70]. To investigate the propagation of variability throughout the risk assessment model, the "mcratio" function was used to calculate the variability ratio for each of the parameters of interest.

2.9 Intervention impact testing

Using the base model, we then tested the relative reduction in infection risk of several interventions independently targeting the transmission pathways (i.e. hand hygiene, surface disinfection, facemask type and usage). Interventions were selected based on the FDA's Food Safety and Modernization Act Produce Rule[66,97] for hand hygiene and surface disinfection guidelines for mitigating worker infection risk. In addition, guidelines from the CDC [63,64] and WHO[79] on face coverings and social distancing specific to the SARS-CoV-2 pandemic were implemented. For the hand hygiene intervention, we leveraged the FSMA guidelines for hand washing and glove use compliance. The hand washing efficacy was defined as a 2-log reduction, with the frequency of handwashing defined as one cleaning event per hour. In the transportation scenario, the hand washing efficacy was adjusted to a 3-log reduction to modulate the use of hand sanitizer once while in the transportation medium. Similarly, the frequency of glove changes was defined as one exchange event per hour.

To assess the impact of surface disinfection on reducing fomite-mediated infection risk, the EPA N-List of SARS-CoV-2 disinfectants was utilized and defined a 3-log reduction as the surface cleaning efficacy. The log reduction in viral particles per handwashing and surface disinfectant event was converted into a percent reduction, which was applied in a modified calculation of C_{hand}. This equation was further modified if glove use followed handwashing to account for viral transfer from contaminated hands to clean gloves, as well as glove exchange frequencies. For the surface disinfection intervention there was both frequency and efficacy of cleaning considered. Frequency of disinfection was evaluated from hourly to every four hours.

Clinical and laboratory-based studies were used to characterize the impact of cloth, surgical, and optimal-fit N95 masks on reducing the number of infectious particles released into the environment from the infectious source and inhaled by the susceptible individual. In subsequent risk reduction calculations, it was assumed that both the infected and susceptible worker would be wearing the specified mask type. Furthermore, to assess the impact of increasing the air exchange rate per hour (ACH) on reducing the risk of infection, the ACH was increased relative to a plausible situation in the residential, transportation, and indoor packaging facility scenario. Representative of opening a window, the ACH in the residential module was increased from 0.35 to a range of 1.98-5.82 with a uniform distribution[98]. For the transportation module, ACH was increased from 0.92-1.60 to 0.92-71.0 with a uniform distribution and is representative of a car being parked, to reaching speeds of 20mph with all windows being fully open[87]. Finally, the ACH for the indoor packaging scenario was increased from 2.0, to a point estimate of 10 air exchanges per hour, based on CDC Guidelines for Environmental Infection Control standards[99].

3. Modeling Results

A quantitative microbial risk assessment model was developed in R to evaluate the risk of SARS-CoV-2 infection among essential food workers. Parameters were collected through extensive literature reviews across empirical, clinical, and modeling studies (Table 1a-c). Three unique viral transmission pathways were assessed, which included aerosols (diameter <50μm), close-contact droplets (diameter >50μm), and fomite-mediated transmission (Figure 1). These pathways were assessed across four scenarios relevant to an essential food worker, namely, shared transportation, shared residential housing, an outdoor harvesting field, and an indoor produce packaging facility (Figure 1). The impact of various face mask materials, hand hygiene compliance, glove utilization, and increased air exchange rates were assessed individually and in combination to determine their effectiveness at reducing SARS-CoV-2 infection risk. Finally, sensitivity analyses were conducted to assess the accumulation of variability across model iterations.

3.1 Risk of Infection in Transportation Medium

As discussed previously, essential food workers have been characterized as engaging in shared transportations to travel to and from their place of work. To investigate the impact of shared transportation on an essential food worker's infection risk, the aerosol and aerosol-contaminated fomite-mediated risk associated with one hour of exposure to an infected individual in a vehicle was modeled. The risk of infection from inhaling aerosolized viral particles accumulating in the air environmental reservoir was determined to be 0.551 (95% CI: 0.121, 0.987), while the fomite-mediated infection risk of 5.05×10^{-12} (95% CI: 4.66×10^{-13}, 1.98×10^{-11} (Figure 2A). These results suggest that the small volume of air available within a vehicle may act to concentrate aerosolized particles, leading to an increased risk of infection from these small-diameter particles.

3.2 Risk of Infection in Residential Area

Migrant and seasonal essential food workers are commonly expected to share residential spaces throughout the harvesting season. To characterize the implications of these expectations on SARS-CoV-2 infection risk, the impact of aerosols, droplets, and virally contaminated fomites was assessed after ten hours of exposure within a shared residential space. The workers were assumed to spend two of the ten hours <2m apart from one another, with the other eight hours spent >3m apart while sleeping. The combined risk of infection across each aerosol, close-contact droplet, and fomite-mediated pathways was calculated to be 0.902 (95% CI: 0.225, 1.00) (Figure 2B). Across the ten hours, the risk attributed to aerosols (0.677, 95% CI: 0.194, 0.999) and close-contact droplets (0.226, 95% CI: 0.031, 0.680) remained considerably higher than the fomite-mediated transmission risk. The results suggest that a substantial level of risk can be attributed to shared housing among essential food workers and particularly emphasize the risk attributed to extended periods of time exposed to infectious aerosols.

3.3 Risk of Infection in Outdoor Harvesting Field

Many produce commodities rely on essential food workers to harvest and sort the items in the outdoor growing fields prior to their shipment to a produce processing facility. Given the close proximity required to complete the harvesting and sorting tasks, the impact of 1m and 2m close-contact droplets and droplet-contaminated fomites on infection risk was assessed across a twelve-hour shift in an outdoor agricultural field. The combined risk associated with droplets and a droplet-contaminated fomite at 1m after twelve hours was 0.149 (95% CI: 0.018, 0.484), whereas the combined risk associated with droplets and a droplet-contaminated fomite at 2m after twelve hours was 0.002 (95% CI: 1.71×10^{-4}, 6.10×10^{-3}) (Figure 2C). The fomite-mediated infection risk remained negligible, as a fomite within 1m of an infection individual yielded a risk of 6.86×10^{-5} (95% CI: 5.75×10^{-6}, 2.76×10^{-4}). Consistent with infection mitigation recommendations, these results support that increasing the distance between workers can decrease infection risk considerable, as shown through a 98.7% reduction in risk after increasing the distance between outdoor workers from 1m to 2m.

3.4 Risk of Infection in Indoor Packaging Facility

Following field harvesting, produce commodities are commonly shipped to packaging and processing facilities prior to retailor distribution. Indoor packaging facility workers commonly complete their work in close proximity on conveyor belt lineups, as such, the risk associated with aerosols, 1m and 2m droplets, and fomite-mediated transmission was characterized after a twelve-hour shift in an indoor packaging facility. The combined risk across the aerosol, close-contact droplet, and representative fomite-contaminated pathways at 1m was calculated to be 1.00 (95% CI: 0.560, 1.00) (data not shown), while the combined risk at 2m was 0.129 (95% CI: 0.015, 0.445) (Figure 2D). Notably, the risk attributed to aerosolized particles (0.063, 95% CI: 0.007, 0.219) was comparable to the risk attributed to 2m close-contact droplets (0.066, 95% CI: 0.008, 0.227). These results suggest that after physically distancing from 1m to 2m, small-diameter aerosols seem to have a similar impact on infection risk as the larger droplets, further emphasizing their potential importance in SARS-CoV-2 transmission dynamics.

3.5 Effects of Face Masks on Reducing Infection Risk

A fundamental SARS-CoV-2 infection mitigation recommendation by the CDC has been to wear face masks while outside of your home. With an increasingly diverse array of face mask types, we assessed the influence of three unique face mask materials (cloth, surgical, optimal-fit N95) on reducing aerosol and close-contact droplet infection risk in each applicable scenario. Relative to no intervention, the risk reduction patterns for each mask material were consistent across the transportation (Figure 3A), residential (Figure 3B), outdoor (Figure 3C), and indoor scenarios (Figure 3D). Percent reductions in risk attributed to cloth (69.2-82.7%), surgical (78.5-88.8%), and optimal-fit N95 (99.5-99.8%) masks varied slightly across each modeled scenario, with the residential scenario displaying the lowest percent reduction for each mask material. These results provide further support for the continued utilization of face masks as an optimal and accessible SARS-CoV-2 infection mitigation intervention.

3.6 Effects of Hand Hygiene Interventions on Reducing Infection Risk

While the impact of fomite-mediated transmission of SARS-CoV-2 continues to be characterized, hand hygiene practices have remained an effective way to reduce infectious materials from contaminated hands. As such, the impact of hand hygiene and glove compliance were explored to understand their role in decreasing the fomite-mediated infection risk within each scenario. Relative to no intervention, the risk reduction patterns for glove use only, handwashing only, and a combination of the two were consistent across the transportation (Figure 4A), residential (Figure 4B), outdoor (Figure 4C), and indoor scenarios (Figure 4D). While the percent reduction in risk attributed to glove use ranged from 22.3-22.5% across the residential, outdoor, and indoor scenario, this intervention was the most impactful at reducing risk in the transportation scenario by 61.2% to 1.96×10^{-12} (95% CI: 1.57×10^{-13}, 8.07×10^{-12}). Although the risk associated with fomites across each modeled scenario was negligible, these findings are consistent with hand hygiene and glove use recommendations to reduce the potential risk of fomite-mediated infection.

3.7 Effects of Surface Disinfection Interventions on Reducing Infection Risk

It is common practice during food preparation and handling to reduce the risk of foodborne pathogen infection through surface disinfection practices; however, the frequency of these disinfection events varies across food and agricultural industries. Thus, relative to no surface disinfection, the impact of disinfection event frequency (daily, every four hours, bihourly, and hourly) on reducing fomite-mediated infection risk was assessed in the outdoor field (Figure 5A) and indoor packaging (Figure 5B) scenarios. Comparable across both outdoor and indoor scenarios, there was an inverse relationship between surface disinfection event frequency and fomite-mediated infection risk. When implemented daily, surface disinfection reduced fomite-mediated risk by 4.1% in the outdoor harvesting field and 4.2% in the indoor packaging facility. As frequency increased to every four hours (69.3% reduction), bihourly (89.4% reduction), and hourly (99.9% reduction), the reduction in risk across both the outdoor agricultural field and indoor packaging facility became equivalent. Although the risk attributed to fomite-mediated infection is small in comparison to aerosols and droplets, these results suggest that the frequency of surface disinfection events can substantially decrease the risk of fomite-mediated infection.

3.8 Effects of Increased Air Exchange Rates on Reducing Infection Risk

In the healthcare setting, one common approach to reducing the number infectious particles accumulating in the air is to implement ventilation systems with high air exchange rates (ACH). While improved ventilation systems have shown to be effective in the healthcare setting, we sought to investigate the impact of situationally appropriate increases in ACH in the transportation, residential, and indoor packaging scenario. In both the transportation and residential scenario, increased ACH was modeled to simulate the opening of all windows in the vehicle or the opening of a single window within the residential space, respectively. For the indoor facility, ACH was increased sequentially from 2.00 to 10.0 to modulate the potential capabilities of industry ventilation systems (Figure 6). The impact of increased ACH was variable across transmission route, as an increase to 10.0 in the indoor facility resulted in a 27.5% reduction for 1m close-contact droplet, 72.2% reduction for 2m close-contact droplet, and a 74.1% reduction in aerosol transmission risk. Situational increases in ACH reduced aerosol and close-contact droplet infection risk substantially by 80.9% in the transportation scenario (0.105, 95% CI: 6.28×10^{-3}, 5.51×10^{-1}) and 54.6% in the residential scenario (0.410, 95% CI: 0.050, 1.00) (data not shown). These results suggest that increasing air exchange rates across each scenario could substantially decrease the risk of SARS-CoV-2 infection; however, the relative impact of this intervention varies based on the transmission route of interest.

3.9.1 Daily Cumulative Risk based on Contact Location

As previously discussed, the four modeled scenarios were constructed to simulate a 24-hour period that could be experienced by an essential food worker. Furthermore, the overarching goal of this approach was to identify potential situations that could attribute to the greatest risk of SARS-CoV-2 infection if an infected and susceptible worker came into contact. Cumulative infection risks were combined across scenarios using an established inclusion-exclusion approach. Across each individual scenario, the risk of infection ranged from 12.9% (indoor packaging facility) to 90.4% (shared residential space), with the outdoor harvesting field (14.9%) and shared transportation (55.1%) scenarios falling within this range. If a susceptible worker shared their morning transportation method with an infected worker and subsequently worked together in an indoor packaging facility, the risk of SARS-CoV-2 infection was 0.680 after 13 hours of cumulative exposure (Table 3). Conversely, if these workers instead worked in an outdoor harvesting field, the risk of SARS-CoV-2 infection was 0.700 after 13 hours of cumulative exposure. Additional scenario combinations (morning and evening carpooling with and without sharing a residential space) included in Table 3 resulted in a calculated risk of 1.00. These findings highlight the variable risk of SARS-CoV-2 infection across each scenario, with the residential and transportation scenarios resulting in the greatest risk of potential infection, while occupational risks are comparably lower.

3.9.2 Daily Cumulative Risk based on Intervention Package Implementation

While the individual impact of various interventions on reducing infection risk have been previously characterized, it is likely that multiple interventions will be applied throughout a given scenario. To understand the combined effect of various interventions on reducing the cumulative risk of infection across all four scenarios, we modeled four unique intervention packages based on current industry standards. Each intervention package included hourly handwashing (H.W.) and surface disinfection (S.D.), with the first intervention package (IP1) incorporating the situational increases in ACH while the second package (IP2) incorporated cloth mask utilization (Table 4a). Intervention package three (IP3) assessed the combined effect increased ACH and cloth masks, while intervention package four (IP4) incorporated a private housing addition to the residential scenario (Table 4b). Relative to no intervention across IP1 and IP2, a percent reduction in daily risk ranging from 23.1-37.6% for an outdoor field worker and 34.5-38.1% for an indoor packaging facility worker was observed (Table 4a). The greatest risk reduction for IP1 was found in the transportation scenario (80.9%), while IP2 had the greatest reduction in the indoor packaging facility (82.7%). Across IP3 and IP4, relative to no intervention the percent reduction in risk ranged from 84.4-90.0% for an outdoor field worker and 86.6-92.1% for an indoor packaging facility worker (Table 4b). The greatest risk reduction for IP3 was observed in the transportation scenario (96.2%), while IP4 had the greatest reduction in the shared residential space (96.5%). These results suggest that the combined effect of implementing intervention packages throughout a 24-hour period of prolonged contact between an infectious and susceptible worker is capable of reducing the risk of infection below 10.0%.

3.9.3 Sensitivity Analyses

Spearman rank correlation coefficients were calculated to identify the parameters that were most influential in the final SARS-CoV-2 infection risk estimate. The parameters identified as increasing the risk of SARS-CoV-2 infection were the viral shedding rate per hour (rho = 0.85), salivary virus concentration in the infected worker (rho = 0.76), frequency of coughing (rho = 0.30), and the susceptible worker inhalation rate (rho = 0.16) (Supplemental Figure 1, Supplemental Table 2). The parameters identified as decreasing the risk of SARS-CoV-2 infection were the susceptible worker's cloth mask protection (rho = -0.42), the infected worker's cloth mask protection (rho = -0.16), and the air exchange rate per hour (rho = -0.15). These results suggest that the propagation of variability throughout the model attributed to parameter heterogeneity was minimal, with a calculated variability ratio of 7.62.

4. Discussion

The goal of this study was to characterize the impact of three SARS-CoV-2 transmission pathways on the daily cumulative risk of infection experienced by an essential food worker. We also sought to determine the effectiveness of CDC recommended and FSMA required infection mitigation interventions when applied individually and in combination. Overall, these results demonstrate that the risk of SARS-CoV-2 infection is influenced by the location of effective contact, be it in a transportation, residential, outdoor field, or indoor facility scenario. Furthermore, the risk of SARS-CoV-2 infection across the aerosol, close-contact droplet, and fomite-mediated transmission pathways are differentially reduced based on the type of intervention, with the greatest risk reduction observed when interventions are applied in combination. These results highlight the increased risk of SARS-CoV-2 infection experienced by essential food workers based on the nature of their work, while further emphasizing the effectiveness of infection mitigation strategies that can be applied to these worker populations.

4.1 Risk of SARS-CoV-2 Infection is Influenced by Location of Effective Contact

Our model has demonstrated that the risk of SARS-CoV-2 infection is influenced by the location of potential transmission, the duration of contact, and the distance between infectious and susceptible workers. With a small volume of space available for viral particles to accumulate upon forced exhalation, shared modes of transportation pose a large risk of infection over a short duration of time. After one hour of exposure in a car, we reported an infection risk of 55.1% based solely on aerosol particles that are capable of accumulating in the space within the vehicle. These results are consistent with the findings of Lan et al.[29], who has reported an increased risk of occupational exposure to SARS-CoV-2 for drivers and transportation workers. Furthermore, these results align with and support recent CDC guidance for agricultural workers[100] detailing that shared modes of transportation may increase the risk of transmission. The significance of characterizing the risk associated with transportation-related SARS-CoV-2 infection is of particular importance for essential food workers given that many workers report using some form of shared transportation to travel to work. In a 2016 study investigating the results of the 2008-2012 National Agricultural Workers Survey, Reid et al.[26] reported that out of 8,698 farmworkers, roughly 31.4% reported utilizing shared transportation methods (carpooling, work bus, raitero) to travel to their place of work. With almost one-third of workers included in that study reporting their reliance on shared transportation methods, this modeled scenario serves as a potential target for future intervention implementation.

Emphasizing the impact that the duration of contact with an infected individual is of comparable importance to the proximity of contact, the risk of infection for the residential scenario was driven predominantly by the accumulation of aerosolized particles within the environment. The risk attributed to aerosolized particles alone accounted for 75.1% of the overall cumulative risk, while that of the 2m close-contact droplets contributed 24.9%. Although increasing the distance between an infected and susceptible individual would inherently decrease their risk of infection through close-contact droplets, these results highlight the contribution of smaller aerosols to overall infection risk due to their ability to remain suspended for extended periods of time. Further compounding to increase the total risk of transmission in the residential scenario are the low ventilation rates reported in some worker-provided housing locations[24]. Early et al.[101] has demonstrated that for farmworker families surveyed in North Carolina, 42.7% reported a window being permanently shut and 47.9% reported there was no air conditioning present in their residential space. With a lack of fresh air circulating within the housing area and removing infectious aerosols from the environment, we are able to observe the effect of lingering aerosols on increasing the risk of SARS-CoV-2 infection over long durations of time.

For essential workers employed at indoor packaging facilities, we have estimated the risk of infection without interventions was maximized at the 1m distance, while implementing social distancing behaviors decreased the risk by 87.1%. It is important to note that while the risk of infection was maximized at the 1m distance, the contribution of fomite-mediated risk was negligible given that fomites contributed 0.01% of the total risk at 12 hours of exposure. These results align with the Pitol et al.[52] risk estimations for community-based transmission of SARS-CoV-2 through contaminated fomite surfaces, with a median risk of 1.60e-4 for their highest risk scenario. Although there are expected to be viral particles contaminating all aspects of the environment surrounding an infected individual (air, fomites, etc.), our model demonstrates that the risk of infection is the highest for aerosol and droplet-based transmission. Additionally, these aerosol and droplet-mediated risks of infection are consistent with documented outbreaks occurring in meat packaging facilities in the United States and Germany[13,14,102]. With the demanding physical labor that prevents some workers from maintaining a six-foot distance between one another, these elevated infection risks further emphasize the importance of implementing CDC risk mitigation recommendations.

While essential outdoor agricultural workers have been documented as experiencing increased risks of heat-related injuries and dehydration[95], there have been no prior investigations to quantify their risk of SARS-CoV-2 infection. Our model has predicted that at 1m distance, the risk of infection for an outdoor agricultural worker is 14.9% after a 12-hour shift. This is similar to the 2m risk for an indoor facility worker of 12.9% after 12-hours; however, it should be noted that this difference could be attributed to varying assumptions between air exchange rates between the indoor and outdoor scenarios. Due to the fluctuating environmental conditions associated with the outdoor environment, it is possible that our risk estimate is a conservative approximation given that the minimum windspeed modeled in this scenario was 5mph. As such, we would expect the viral particles to quickly be removed from the region of space surrounding these agricultural workers at greater rates than found in any other modeled scenario, thereby reducing their infection risk substantially. As previously modeled by Zhang et al.[39], we would expect the contrary to hold true; when air exchange rates decrease (or in this case, wind speeds decrease), the risk of infection would increase as a result. Thus, while our modeled scenario should serve as an approximation for the risk of SARS-CoV-2 infection that an outdoor agricultural worker could be exposed to, environmental conditions like wind speed could also play a role in either increasing or decreasing this risk.

4.2 Risk of SARS-CoV-2 Infection is Differentially Reduced by Intervention Type

Our model has predicted that fomite-mediated transmission of SARS-CoV-2 in the essential food worker population seems to pose minimal risk when compared with other modes of transmission. Regardless, it is of great importance to understand and quantify risk reduction strategies that could drive infection risk even lower. Our fomite-mediated transmission pathway was subject to intervention implementations that align with the existing Food Safety Modernization Act (FSMA) requirements, such as surface disinfection, glove usage, and hand hygiene compliance[66]. Across each of our modeled scenarios, compliance with the hand hygiene intervention yielded a greater reduction in risk than glove usage alone. One potential explanation for this finding is that our model assumes a uniform distribution between 0 and 44.4% of the pathogen could be transferred from an already contaminated hand to the fresh glove during the gloving process. This process has been documented by Rönnqvist et al.[81] with the transfer of norovirus from artificially contaminated hands to latex gloves. As such, our model assumed that this transfer process could also be applied to SARS-CoV-2 during the gloving process to maintain a worst-case scenario approach while more research is being done on the pathogenic properties.

Routine surface cleaning with EPA-approved[80] SARS-CoV-2 disinfectants reduced the risk of fomite-mediated infection equally in both the indoor packaging and outdoor harvesting scenarios. With no surface disinfection intervention serving as our baseline, the most effective disinfection strategy was hourly cleaning, which reduced fomite-mediated infection risk by 99.9%. Conversely, enacting a once-per-shift surface disinfection routine reduced fomite-mediated infection risk by merely 4.2%. These results demonstrate that surface disinfection strategies would have the greatest efficacy at reducing infection risk when enacted bihourly or hourly, with moderate efficacy when enacted every four hours (69.3% reduction). Even so, the application of these disinfection strategies should be carefully evaluated and implemented in such a way that avoids increasing potentially infectious contact through the aerosol and droplet-mediated transmission routes.

The predominant infection mitigation recommendation supported by both the CDC and WHO to date has been face mask utilization[63,79]. Our model has identified this strategy as being one of the most efficacious at reducing infection risk, with risk reductions being dependent on the face mask material. Aligning with previous mask efficacy experiments performed by laboratory[75,78] and clinical studies[103], the most efficacious face mask was an optimally-fit N-95 respirator mask, followed by surgical and cloth masks, respectively. While N-95 masks remain the most effective at preventing infection, these masks are likely not representative of the types of mask present or accessible to essential food workers. Recent farmworker studies performed in Oregon and California have demonstrated that the most common form of face mask material provided by employers have been cloth masks, followed by disposable surgical masks[86,104]. It is important to note that these studies have also identified inequities in the distribution of these face masks, with some employers refusing to provide face masks of any type to their workers. As such, it remains integral to identify strategies that can be implemented in these essential populations to lessen the disproportionate risk they endure.

Interestingly, the reduction in risk conferred by utilizing each type of face mask differed depending on the scenario being modeled. For example, the cloth mask had a reduction in risk ranging from 71.1% in the transportation scenario to 82.7% in the indoor packaging facility. This observation could potentially be attributed to the transmission pathways that were assessed in each scenario. Throughout the shared transportation scenario, our model assessed the aerosol and aerosol-contaminated fomite risks of infection, whereas in the packaging facility scenario, we assessed both aerosol and droplet-mediated infection pathways. These results suggest that cloth masks may be better at reducing the number of infectious droplets released into the environment from an infected individual rather than the small-diameter aerosols. This is consistent with the findings in Konda et al.[76], where cloth masks were most effective at filtering droplets >300µm in diameter than droplets and aerosols <300µm in diameter, regardless of the number of cloth layers. Although it was not investigated in the present study, future work should analyze the effects of discordant mask wearing between the susceptible and infected individual.

As discussed in Morawska et al.[105], an underexplored SARS-CoV-2 infection mitigation strategy centers around increasing the air exchange rate in a particular space. Although increasing air exchange rates have been documented as decreasing the risk of infection for other respiratory pathogens like tuberculosis[106], this effect remains unexplored in relation to SARS-CoV-2. Our model sought to investigate the role of increasing air exchange on decreasing infection risk based on situational-appropriate and accessible strategies. Excluding the outdoor scenario, the increased air exchange intervention resulted in a substantial decrease in cumulative infection risk for each modeled scenario.

For both the transportation and residential scenarios, the method employed to increase the air exchange rate was through the opening of windows. This seemingly simple intervention inherently allowed for larger volumes of virally contaminated air to be removed from the modeled space, thereby reducing the concentration of virus and, as a result, the infectious dose inhaled by the susceptible individual. Given the large proportion of food workers reporting shared housing and transportation methods to work, increasing air exchange rates in these scenarios could potentially serve as an effective and accessible risk mitigation strategy.

The role of Heating, Ventilation, and Air Conditioning (HVAC) systems, when implemented properly in facilities like the indoor packaging scenario, could decrease the risk of infection for facility workers[105]. By increasing the air exchange rate from 2 per hour to 10 per hour, we observed a 73.2% cumulative reduction in infection risk at 2m, and a 25.2% reduction at 1m distances, respectively. Furthermore, the reduction of aerosol-mediated infection risk at 1m was 74.1%, whereas the droplet-mediated infection risk was only reduced by 27.5% at 10 air exchanges per hour. These findings highlight the relationship between air exchange rate and the removal of respiratory particles released into the environment. Respiratory droplets have been shown to follow ballistic trajectory paths when forcefully expelled due to their increased volume when compared to smaller diameter aerosol particles[46]. As such, these particles would be expected to quickly fall out of the air environmental reservoir by the 3m distance. Conversely, the respiratory aerosol particles would be expected to remain suspended in the air for longer durations of time. Consistent with our findings, we would therefore expect the aerosol particles that remain suspended and be more heavily impacted by the removal of air over time when compared to their larger droplet counterparts. Thus, our results suggest that increasing the air exchange rate will decrease the risk of SARS-CoV-2 infection by reducing the concentration of virus-containing particles that a susceptible individual could be exposed to.

We proposed four unique intervention packages that would assess the impact of multiple interventions on decreasing the daily risk for an essential food worker. Given standard hand hygiene and surface disinfection expectations set for by the FSMA[97], each package included hourly handwashing and surface disinfection interventions. To these standards, either the increased air exchange rate (IP1), cloth mask utilization (IP2), both increased air exchange rate and cloth mask utilization (IP3), or the addition of private housing to the previous intervention package (IP4), was assessed. Interestingly, IP1 was found to be more effective at reducing infection risk in the shared transportation scenario than wearing a cloth mask, as modeled in IP2. Conversely, cloth mask utilization in IP2 was found to be more effective at reducing infection risk in the indoor packaging facility and residential space than increased air exchange rates in IP1. This could likely be attributed to the transmission pathways observed in the individual scenarios, with the shared transportation model solely investigating the role of aerosols and not droplets. Consistent with Leung et al.[77], these results suggest that cloth masks may be better at capturing infectious droplets rather than aerosols.

When increased air exchange rates and cloth masks are implemented simultaneously (IP3), we are able to observe the largest reduction in infection risk in the transportation (96.2% reduction) and indoor packaging facility (95.5% reduction) scenarios. These results highlight the synergistic effects of reducing the concentration of viral particles released into and inhaled from the environment, with the increased rate of contaminated air removal, on lowering the risk of SARS-CoV-2 infection. The final intervention package sought to investigate the impact of private sleeping quarters for the essential workers in shared housing in addition to the interventions implemented in IP3. With only 2 hours of potential contact time in the residential scenario, we were able to observe a 96.5% reduction in infection risk when workers were not expected to sleep in the same area. As reported in a California[104], Oregon[24,86], North Carolina[17,21,107], and Washington State[108], crowded housing conditions among agricultural workers has been a problem for many years. Given that the residential scenario alone produced a cumulative infection risk of 90.4% without risk mitigation strategies, our results indicate that shared housing poses one of the largest threats to our essential food worker populations. If we are to protect the health and wellbeing of our essential food worker population, particularly those in shared housing conditions, we must recognize and identify the potential threats and solutions to mitigate their risk of infection.

4.3 Modeling Strengths, Limitations, & Future Directions

Our extensive modeling approach taken to assess the daily cumulative risk of SARS-CoV-2 infection experienced by an essential food worker has notable strengths. We have leveraged findings from peer-reviewed publication regarding the clinical and physical characteristics associated with SARS-CoV-2 transmission, while generating scenarios pertinent to essential food workers based on feedback from food and agricultural industry partners. Utilizing this approach, we were able to critically evaluate the relative contribution of each transmission pathway (aerosol, close-contact droplet, and fomite-mediated) on infection risk, as well as the impact of infection mitigation recommendations on reducing this risk. Finally, the structure of our model lends itself to the creation of future scenarios that could assess scenarios outside the scope of the food and agricultural industry, such as a hospital ward, a classroom, or a mode of public transportation.

As with all modeling studies, there are inherent limitations. The first limitation lies within our assumption that only one symptomatic individual would be present per scenario. Given that a recent systematic literature review by He et al.[109] demonstrated that across 50,155 patients, 15.6% were asymptomatic and infected with SARS-CoV-2, the potential role of asymptomatic transmission through breathing, talking, or even singing remains to be addressed. An additional limitation related to the occupational scenarios being modeled is that our model did not factor in any breaks during a worker's shift. The impact of this omission could result in a slight decrease in the true risk of infection, particularly if the infected and susceptible workers are not on the same break schedule. A final limitation to our model is that we did not account for any time spent outside of the four modeled scenarios. As a result, our model does not account for the possibility of community transmission of SARS-CoV-2 outside of the transportation, residential, and occupational scenario. The incorporation of community-based transmission models, in addition to these scenario-based transmission estimates, would serve as a novel approach to characterizing the true risk of infection for essential food workers.

4.4 Conclusions & Public Health Recommendations

Our model has demonstrated that essential food workers are at an increased risk of SARS-CoV-2 infection due to the nature of their occupation. Unable to engage in certain risk mitigation strategies (paid furlough, social distancing, teleworking, etc.), it is integral to characterize the impact that situationally appropriate interventions could have on reducing their infection risk. These results highlight that the risk of infection for essential food workers is the highest when engaging in shared housing and transportation situations, both of which have become commonplace among seasonal and migrant essential food workers. Increasing worker accessibility to private housing and individual transportation methods would serve as a potential risk mitigation strategy for employers to maintain the health of these workers. Furthermore, improvements in the air exchange rate across all scenarios modeled has shown to decrease the risk of infection. Whether this intervention be incorporated through the lowering of windows to increase natural ventilation, or the installation of HVAC systems designed to remove, and not recycle, potentially infectious air, the outcome of decreasing the infection risk remains.

Our results further emphasize the importance of incorporating CDC infection mitigation strategies, such as mask utilization and social distancing, in reducing aerosol and droplet-mediated transmission. Although the fomite-mediated risk of infection was minimal compared to the other two transmission pathways, the implementation of FSMA requirements proved effective at decreasing this infection risk. When combined in parallel, these risk mitigation guidelines work synergistically to reduce the aerosol, droplet, and fomite-mediated pathways of infection for essential food workers. It is clear that the continued utilization of facemasks and social distancing behaviors would reduce potentially infectious contact between workers. Furthermore, this emphasizes the importance of increasing the accessibility of appropriate face masks to workers, particularly for seasonal and migrant workers that have reported a lack of employer-provided masks[86,104].

If the United States is to remain functional, fruitful, and fed, essential food worker populations must not remain unheard during the pandemic. The expectation for these workers to continue performing their occupational duties while much remains unknown about the SARS-CoV-2 virus emphasizes the importance of maintaining their health and limiting their risk of infection. With the staggered release of vaccinations to essential worker populations, we must not let food workers fall through the cracks created by rurality, technological and linguistic inaccessibility, and governmentally influenced vaccine hesitancy issues. The SARS-CoV-2 pandemic has presented a unique shift in the narrative of how we as a nation prioritize and appreciate certain occupations. Although they have been commonly overlooked, essential food workers are a touchstone population to maintain a prosperous and productive nation. In conclusion, when made available to the essential food worker populations, situationally appropriate interventions serve as an effective strategy to lower infection risk and maintain a functioning society.

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6. Figures & Tables

Table 1a. Model parameters and distributions pertinent to SARS-CoV-2 virus

Class	Parameter	Units	Description	Input Values *	Distribution	Reference
Virus						
	$Log_{10}(C_{virus})$	PFU/mL	Concentration of virus in saliva	6.75 (6.10, 7.40)	Uniform	71,72
	$d_{p,c}$	cm	Diameter of respiratory particles for coughing event	6.0E-4 (2.0E-4, 4.9E-3)	Triangular	36,45,110
	$d_{p,b}$	cm	Diameter of respiratory particles for breathing event	8.0E-5 (3.0E-5, 2.0E-3)	Triangular	37,110
	$V_{F,c}$	$mL/Cough$	Fraction of volume associated with droplet diameters 2µm–50µm	2.3E-6 (1.4E-6, 2.6E-6)	Triangular	110
	$V_{F,c}$	$mL/Cough$	Fraction of volume associated with droplet diameters 50µm–60µm	6.0E-6 (3.5E-6, 6.7E-6)	Triangular	110
	$V_{F,c}$	$mL/Cough$	Fraction of volume associated with droplet diameters 60µm–100µm	4.9E-6 (1.1E-6, 8.4E-6)	Triangular	110
	$V_{F,c}$	$mL/Cough$	Fraction of volume associated with droplet diameters 100µm–750µm	6.8E-3 (4.0E-3, 7.6E-3)	Triangular	110
	$V_{F,b}$	$mL/Breath$	Fraction of volume associated with droplet diameters 0.6µm-2.2µm	2.0E-10 (1.1E-10, 2.9E-10)	Uniform	37,110
	F_C	$Cough/hr$	Coughing rate per hour	24.7 (10.0, 39.3)	Uniform	77
	F_B	$Breath/hr$	Breathing rate per hour	1081 (960, 1,200)	Uniform	111
	λ_{virus}	hr^{-1}	Viral decay of SARS-CoV-2	0.614	Point	74,112

*Values presented as Mean (Min, Max) for Uniform Distributions & Mode (Min, Max) for Triangular Distributions

Table 1b. Model parameters and distributions pertinent to risk mitigation interventions

Class	Parameter	Units	Description	Input Values*	Distribution	Ref.
Interventions						
	$S_{mask(S)}$	Log reduction	Source surgical mask efficacy	0.478 (0.387, 0.569)	Uniform	[75,76,78]
	$S_{mask(R)}$	Percent reduction	Recipient surgical mask efficacy	0.680 (0.370, 0.998)	Uniform	[75,76,78]
	$C_{mask(S)}$	Log reduction	Source cloth mask efficacy	0.466 (0.310, 0.620)	Uniform	[75,76,78]
	$C_{mask(R)}$	Percent reduction	Recipient cloth mask efficacy	0.529 (0.170, 0.887)	Uniform	[75,76,78]
	$N95_{opt(S)}$	Log reduction	Source optimal fit N95 mask efficacy	2.02 (1.89, 2.15)	Uniform	[75,76,78]
	$N95_{opt(R)}$	Percent Reduction	Recipient optimal fit N95 mask efficacy	0.790	Point	[75,76,78]
	SC_{eff}	Log reduction	Surface disinfection percent reduction	3.00	Point	[80]
	HW_{eff}	Log reduction	Hand washing efficacy	2.00	Point	[113]
	HW_{freq}	$^{HW}/_{hr}$	Frequency of handwashing per hour	1.00	Point	Assumed
	G_{freq}	$^{\text{Glove change}}/_{hr}$	Frequency of glove changes per hour	1.00	Point	Assumed

*Values presented as Mean (Min, Max) for Uniform Distributions

Table 1c. Model parameters and distributions pertinent to risk assessment

Class	Parameter	Units	Description	Input Values*	Distribution	Ref.
Risk						
	$F_{12,\,lh}$	Proportion	Proportion of virus transferred from polyester fomite to hand in low humidity	0.003 (0.002)	Normal	91
	$F_{12,\,lh}$	Proportion	Proportion of virus transferred from stainless-steel fomite to hand in low humidity	0.069 (0.00, 0.158)	Triangular	91
	$F_{12,\,hh}$	Proportion	Proportion of virus transferred from glass fomite to hand in high humidity	0.673 (0.250)	Normal	91
	$F_{12,\,hh}$	Proportion	Proportion of virus transferred from stainless-steel fomite to hand in high humidity	0.374 (0.160)	Normal	91
	F_{23}	Proportion	Proportion of virus transferred from hand to face	0.200 (0.063)	Normal	114
	F_{24}	Proportion	Proportion of virus transferred from hand to glove during gloving process	0.221 (0.00, 0.444)	Uniform	81
	L_{dep}	Proportion	Deposition fraction of infectious virus into the lungs	1.00	Point	Assumed
	I_R	m^3/hr	Inhalation rate per hour	2.40 (1.62, 3.18)	Uniform	115
	k_{risk}	Unitless	Dose-response parameter	6.80E-3	Point	52

*Values presented as Mean (Min, Max) for Uniform Distributions, Mode (Min, Max) for Triangular Distributions, & Mean (SD) for Normal Distributions

Figure 1. SARS-CoV-2 QMRA Schematic.

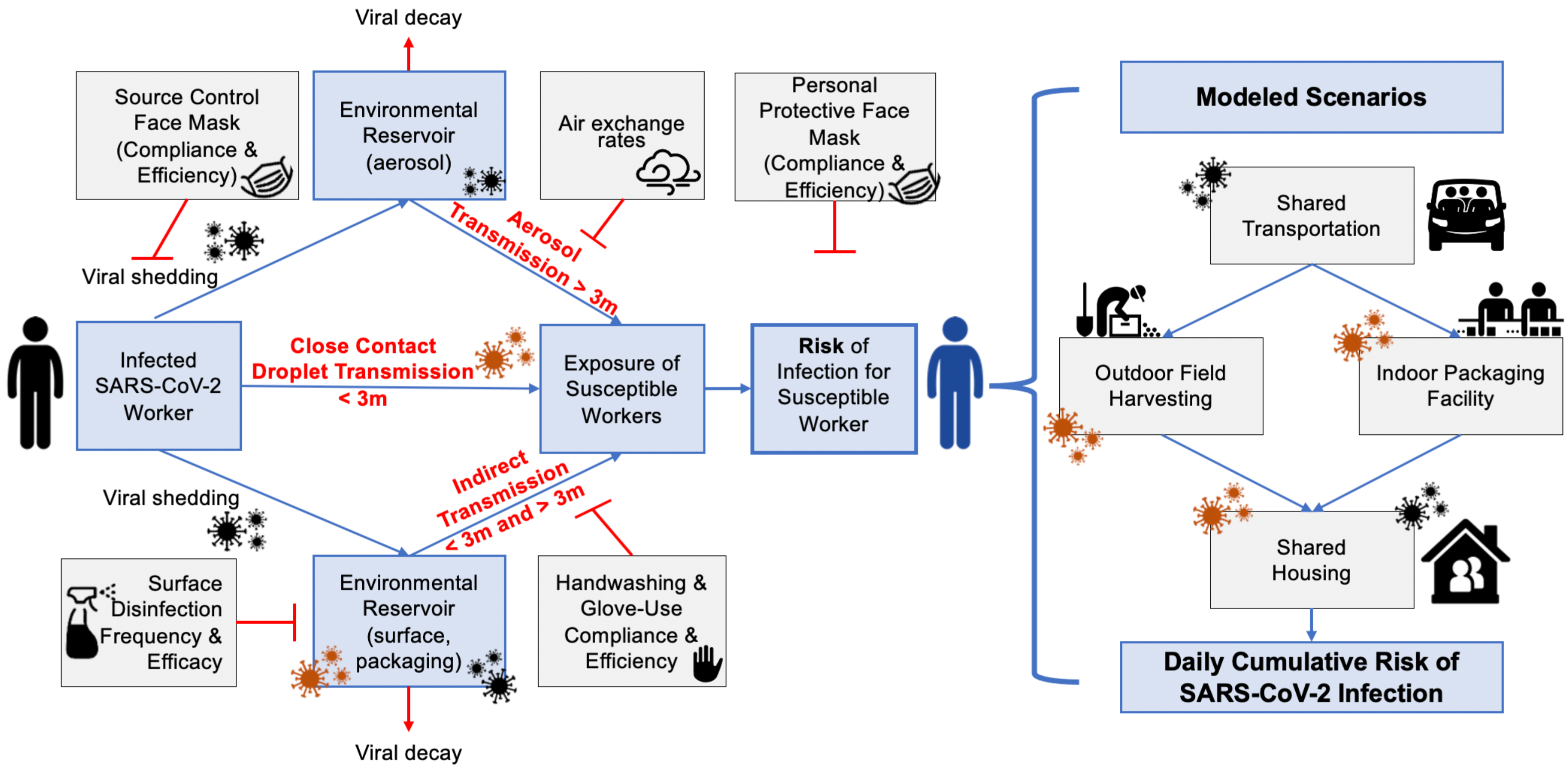


Figure 1. SARS-CoV-2 QMRA schematic for a coughing respiratory event to assess infection risk through three transmission pathways (aerosol, close-contact [droplet and aerosol], fomite-mediated) which were applied to four scenarios relevant to an essential food worker (shared transportation, outdoor field harvesting, indoor packaging facility, shared housing). A coughing event releases both aerosols (particles ranging in diameter from 2-50µm) and droplets (particles >50µm in diameter) which are capable of contaminating a fomite environmental reservoir. Small-diameter aerosols can remain suspended in the air for multiple hours and travel anywhere from 0-8m upon emission. Conversely, large-diameter droplets follow a semi-ballistic trajectory and quickly fall to the ground (or fomite surface) within 3m upon emission. Essential food workers have been documented as partaking in shared modes of transportation to their place of employment, often times while residing in an employer-provided shared housing accommodation. Occupational exposures are of relevance to this worker population due to their inability socially distance while working in outdoor harvesting fields or indoor packaging facilities. The schematic presented was conceptualized and created in partnership with Julia Sobolik, PhD Candidate.

Figure 2. Risk of SARS-CoV-2 infection across four modeled scenarios pertinent to an essential food worker.

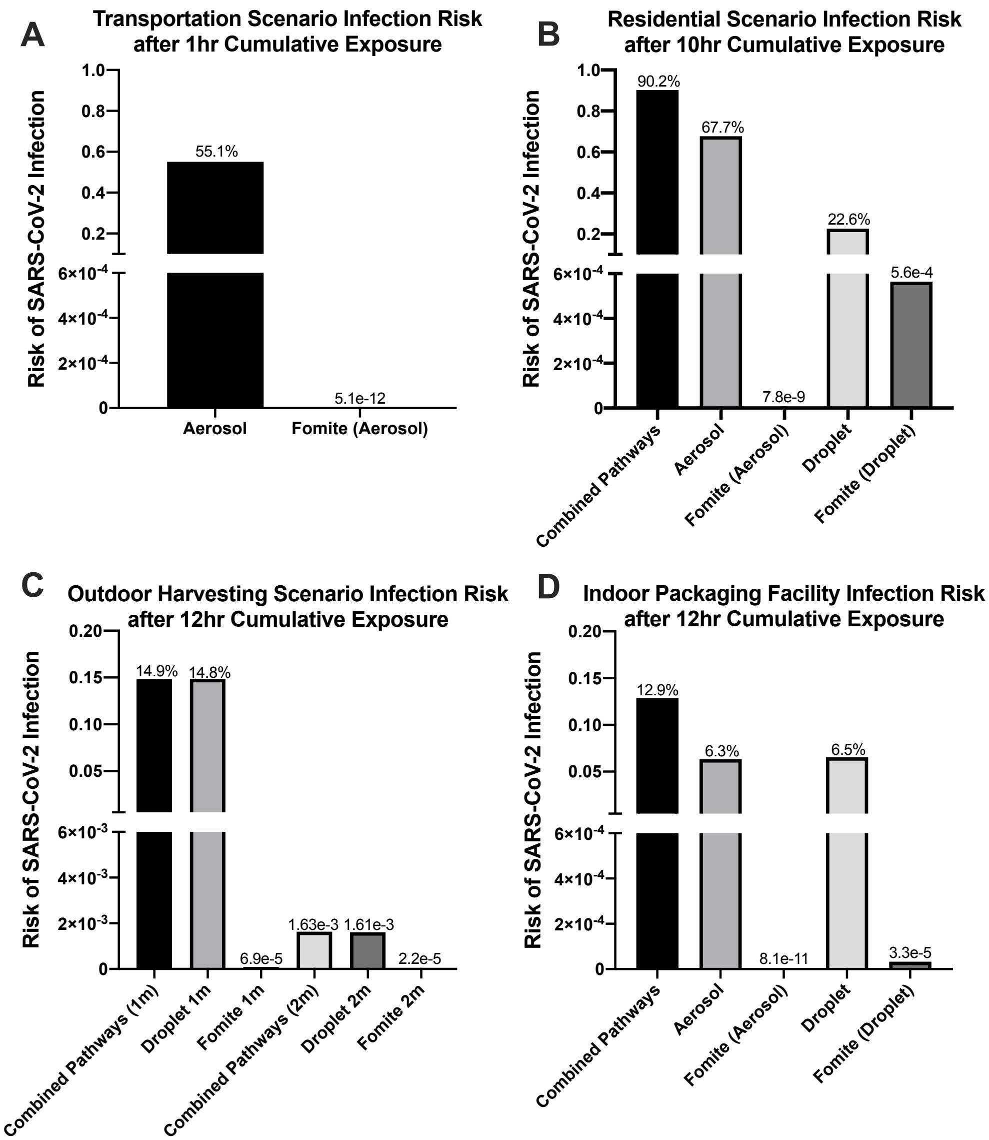


Figure 2. Risk of SARS-CoV-2 infection varies across transmission route (aerosol, close-contact droplet, fomite-mediated) and modeled scenario pertinent to an essential food worker. The Y-axis represents the risk of SARS-CoV-2 infection for a susceptible worker that sustains contact with a symptomatic individual in the (A) shared transportation, (B) shared residential, (C) outdoor agricultural field, and (D) indoor packaging facility scenarios. Denoted below the X-axis, each SARS-CoV-2 transmission pathway assessed per scenario is represented by each respective bar. The risk of infection per transmission pathway is listed above the bar for each scenario.

Figure 3. Reduction in SARS-CoV-2 infection risk attributed to face mask utilization

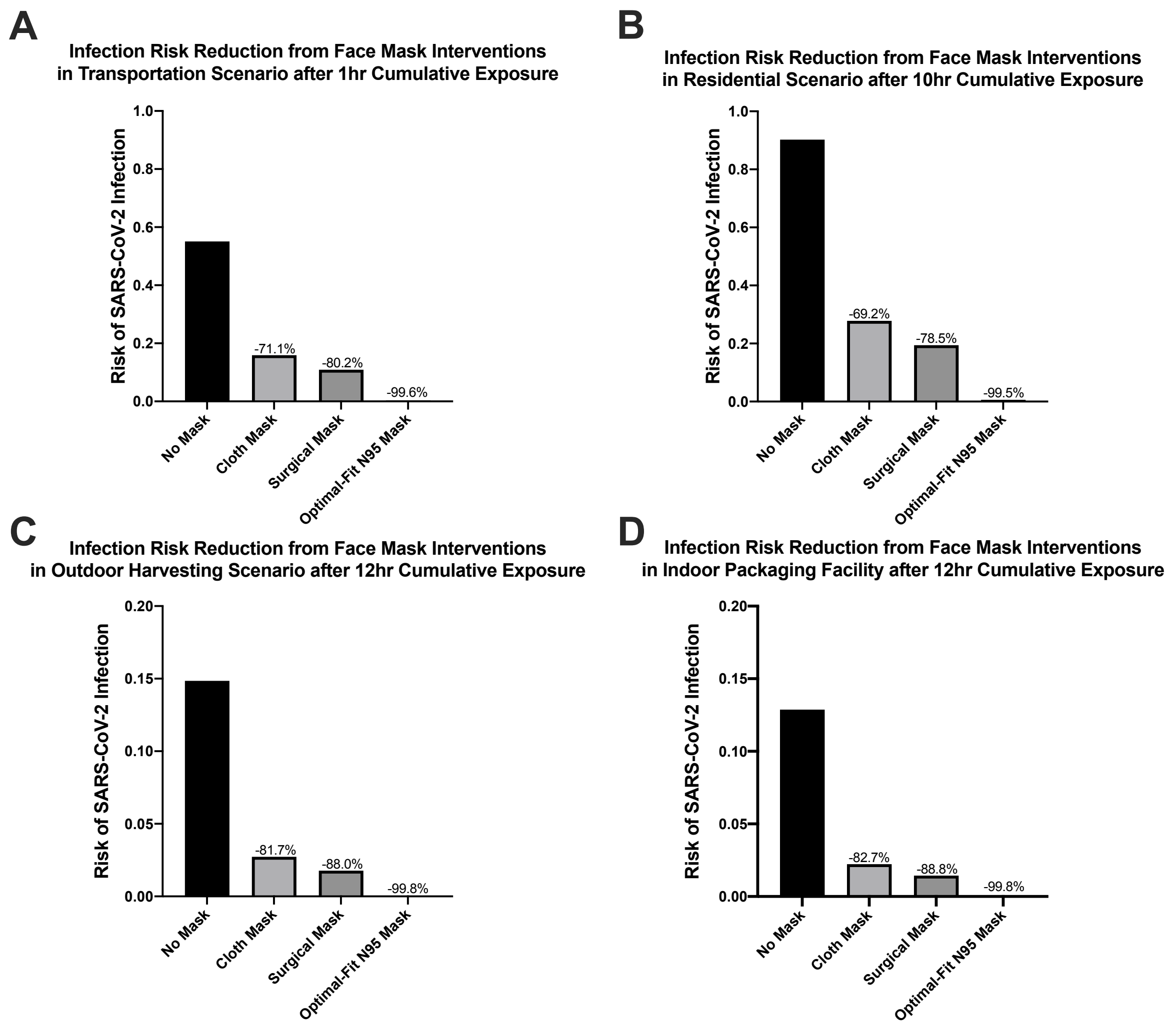


Figure 3. Reduction in SARS-CoV-2 infection risk attributed to face mask wearing by both infected and susceptible workers varies by face mask material (cloth, surgical, optimal-fit N95) per modeled scenario. The Y-axis represents the risk of SARS-CoV-2 infection for a susceptible worker that sustains contact with a symptomatic individual in the (A) shared transportation, (B) shared residential, (C) outdoor agricultural field, and (D) indoor packaging facility scenarios. For each panel, the black bar represents the cumulative risk of infection without any interventions, with each subsequent bar representing the cumulative risk of infection after face mask use across both infected and susceptible worker. Listed above each bar is the infection risk reduction attributed to each face mask type.

Figure 4. Reduction in SARS-CoV-2 fomite-mediated infection risk attributed to hand hygiene interventions

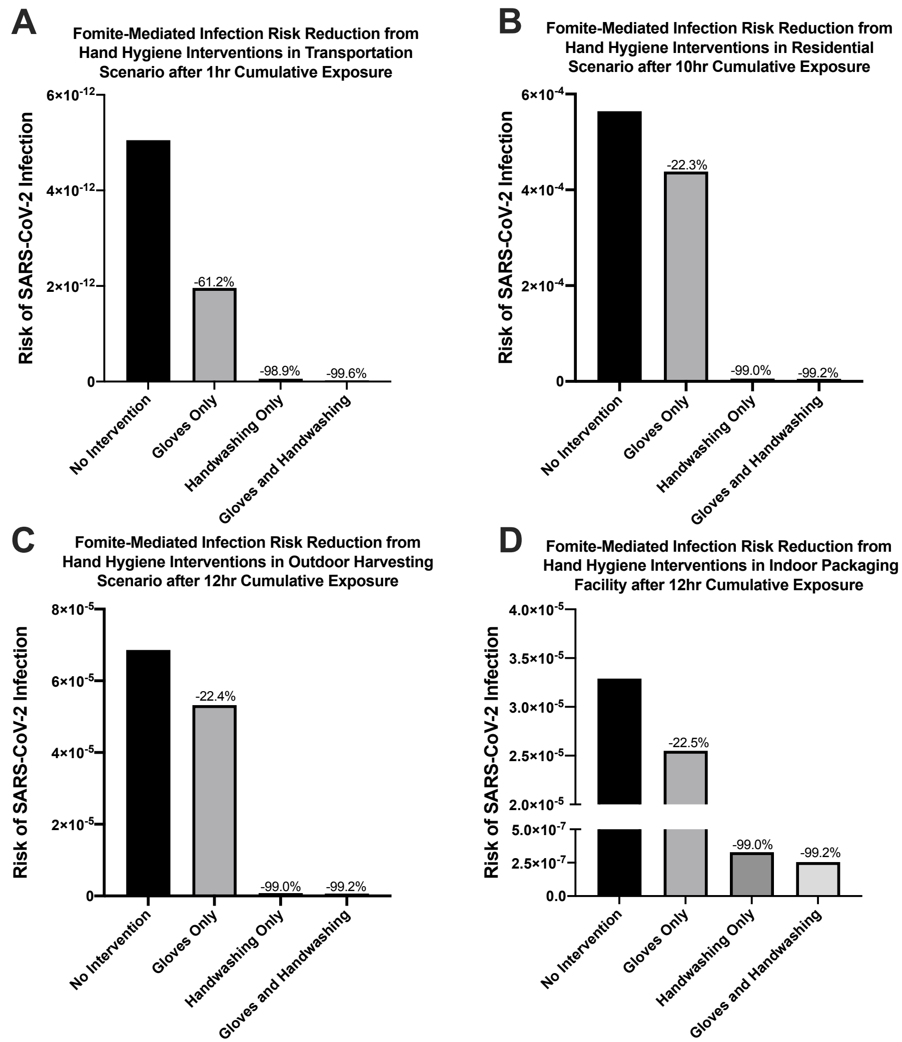


Figure 4. Reduction in SARS-CoV-2 fomite-mediated infection risk attributed to hand hygiene interventions (glove utilization, handwashing practices, or the two in concert) varies by intervention type. The Y-axis represents the risk of fomite-mediated SARS-CoV-2 infection for a susceptible worker that sustains contact with a symptomatic individual in the (A) shared transportation, (B) shared residential, (C) outdoor agricultural field, and (D) indoor packaging facility scenarios. For each panel, the black bar represents the cumulative risk of fomite-mediated infection without interventions and each subsequent bar represents the cumulative risk of infection after hand hygiene intervention implementation. Listed above each bar is the fomite-mediated infection risk reduction attributed to each hand hygiene intervention.

Figure 5. Reduction in SARS-CoV-2 fomite-mediated infection risk attributed to surface disinfection frequency

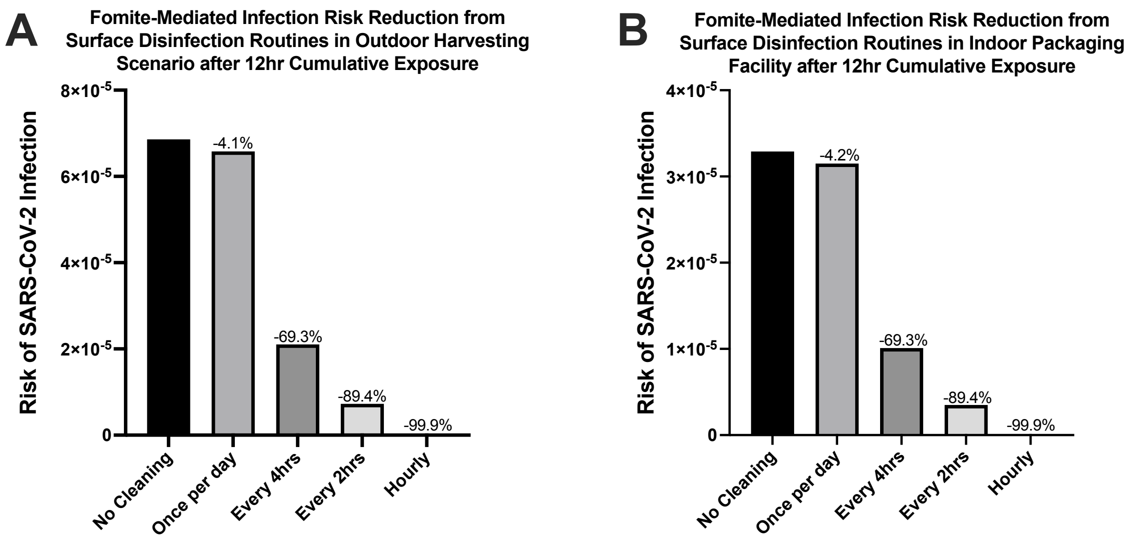


Figure 5. Reduction in SARS-CoV-2 fomite-mediated infection risk varies by surface disinfection frequency (daily, every 4 hours, bihourly, hourly) in the outdoor harvesting field or indoor packaging facility scenario. The Y-axis represents the risk of fomite-mediated SARS-CoV-2 infection for a susceptible worker that sustains contact with a symptomatic individual in the (A) Outdoor Harvesting and (B) Indoor Packaging Facility scenarios. For each panel, the black bar represents the cumulative risk of fomite-mediated infection without interventions and each subsequent bar represents the cumulative risk of infection after surface disinfection with frequency denoted under the X-axis. Listed above each bar is the fomite-mediated infection risk reduction attributed to each frequency of surface disinfection.

Figure 6. Reduction in SARS-CoV-2 aerosol and close-contact droplet risk attributed to increasing the air exchange rate.

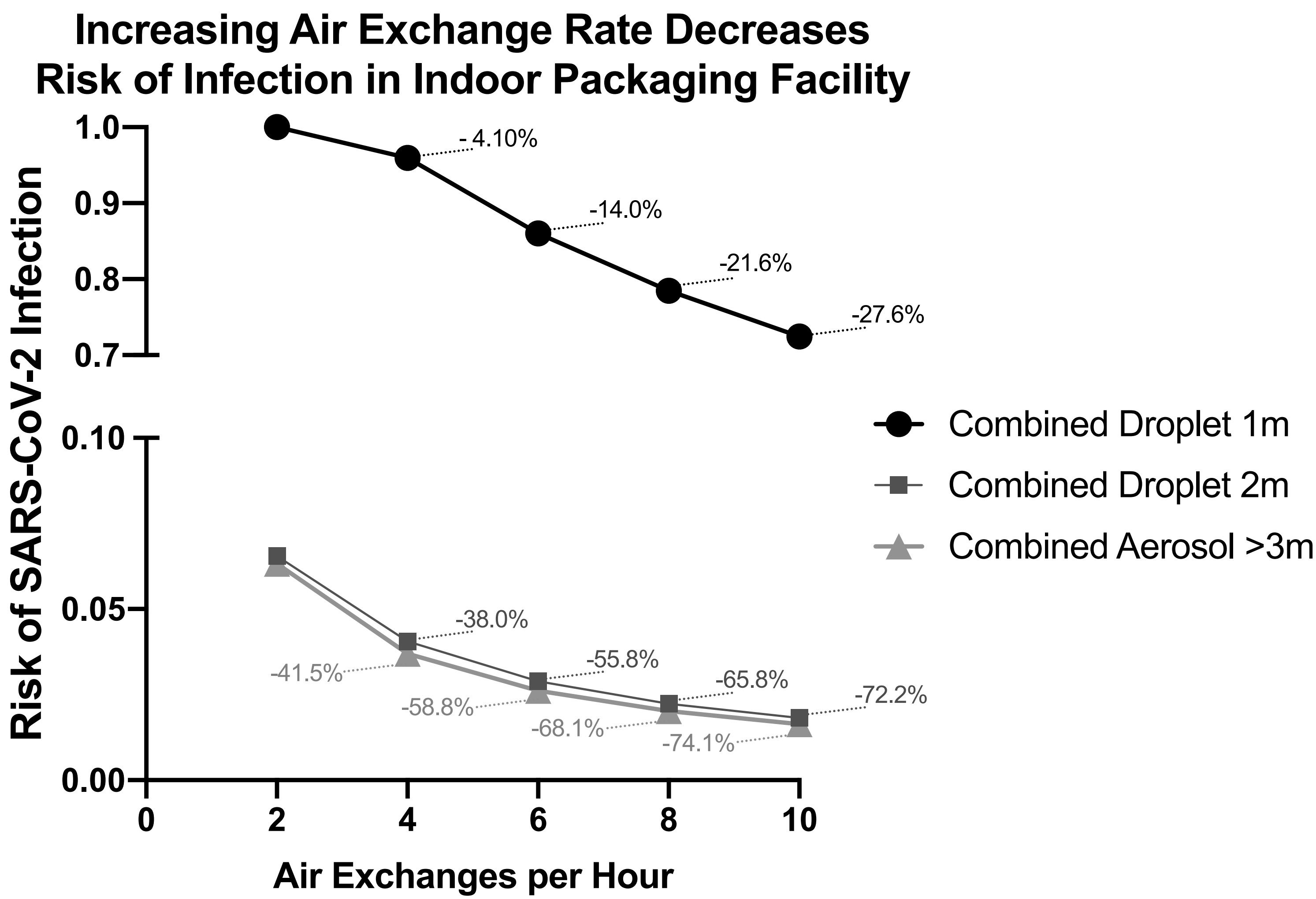


Figure 6. The risk of SARS-CoV-2 infection varies across transmission route (combined droplet and droplet-contaminated fomite at 1-2m, combined aerosol and aerosol-contaminated fomite) and modeled air exchange rate (ACH) in the indoor packaging facility. The Y-axis represents the cumulative risk of SARS-CoV-2 infection for a susceptible worker that sustains contact with an asymptomatic individual in the indoor packaging facility. The X-axis represents the modeled air exchange rate per hour, with each line representing one of three transmission pathways (droplet 1m, droplet 2m, and aerosol >3m). Numerical values indicating the percent reduction in infection risk are denoted for each point on the figure, with the industry standard ACH of 2.0 acting as the reference.

Table 3. Cumulative Risk of SARS-CoV-2 Infection based on Location of Contact

	Morning Transportation	Occupational Location		Evening Transportation	Residential Space	Cumulative Infection Risk
		Indoor	***Outdoor***			
Was there contact between an infected & susceptible individual?	Yes	No	No	No	No	0.551
	No	Yes	No	No	No	0.129
	No	No	Yes	No	No	0.149
	No	No	No	Yes	No	0.551
	No	No	No	No	Yes	0.904
	Yes	Yes	No	No	No	0.680
	Yes	No	Yes	No	No	0.700
	Yes	No	No	Yes	No	1.00
	Yes	No	No	Yes	Yes	1.00

Table 4a. Cumulative Risk of SARS-CoV-2 Infection after Intervention Package 1 & 2 Implementation

	Morning Transportation	Occupational Location		Evening Transportation	Residential Space	Cumulative Risk (% Reduction)
		Indoor	*Outdoor*			
Intervention Package 1:	Yes	No	No	No	No	0.105 (80.9%)
Inc. ACH	No	Yes[a]	No	No	No	0.035 (73.2%)
Hourly H.W. *Hourly S.D.*	No	No	Yes[b]	No	No	0.149 (0.00%)
	No	No	No	Yes	No	0.105 (80.9%)
	No	No	No	No	Yes	0.410 (54.6%)
	Yes	Yes[a]	Yes[b]	Yes	Yes	0.655 (34.5%)[a] 0.769 (23.1%)[b]
Intervention Package 2:	Yes	No	No	No	No	0.159 (71.1%)
Cloth Mask	No	Yes[a]	No	No	No	0.022 (82.7%)
Hourly H.W. *Hourly S.D.*	No	No	Yes[b]	No	No	0.027 (81.7%)
	No	No	No	Yes	No	0.159 (71.1%)
	No	No	No	No	Yes	0.278 (69.2%)
	Yes	Yes[a]	Yes[b]	Yes	Yes	0.619 (38.1%)[a] 0.624 (37.6%)[b]

[a] Cumulative Risk for Indoor Packaging Facility Worker
[b] Cumulative Risk for Outdoor Harvesting Field Worker (not including increased ACH intervention)

Table 4b. Cumulative Risk of SARS-CoV-2 Infection after Intervention Package 3 & 4 Implementation

	Morning Transportation	Occupational Location		Evening Transportation	Residential Space	Cumulative Risk (% Reduction)
		Indoor	*Outdoor*			
Intervention Package 3:	Yes	No	No	No	No	0.021 (96.2%)
Inc. ACH Cloth Mask Hourly H.W. Hourly S.D.	No	Yes[a]	No	No	No	0.006 (95.5%)
	No	No	Yes[b]	No	No	0.027 (81.7%)
	No	No	No	Yes	No	0.021 (96.2%)
	No	No	No	No	Yes	0.087 (90.4%)
	Yes	Yes[a]	Yes[b]	Yes	Yes	0.134 (86.6%)[a] 0.156 (84.4%)[b]
Intervention Package 4:	Yes	No	No	No	No	0.021 (96.2%)
Inc. ACH Cloth Mask Hourly H.W. Hourly S.D. Private Housing	No	Yes[a]	No	No	No	0.006 (95.5%)
	No	No	Yes[b]	No	No	0.027 (81.7%)
	No	No	No	Yes	No	0.021 (96.2%)
	No	No	No	No	Yes	0.031 (96.5%)
	Yes	Yes[a]	Yes[b]	Yes	Yes	0.079 (92.1%)[a] 0.100 (90.0%)[b]

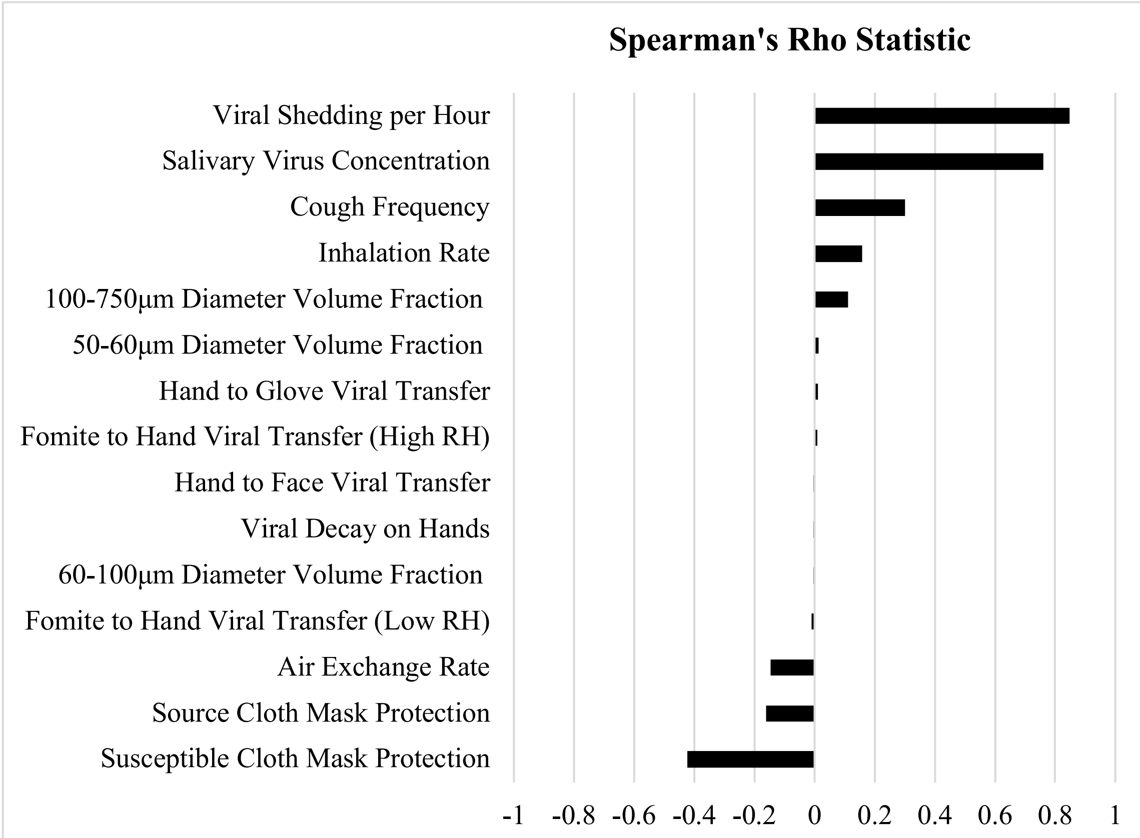
[a] Cumulative Risk for Indoor Packaging Facility Worker
[b] Cumulative Risk for Outdoor Harvesting Field Worker (not including increased ACH intervention)

7. Supplemental Materials

Supplemental Table 1. Calculated air transport model variables for indoor packaging facility

Variable	Units	Description	Input Values
$V_{Facility}$	m^3	Volume of facility modeled	460
d_h	m	Wind Tunnel Diameter	10.0
k_v	m^2/s	Kinematic viscosity of air	1.49E-5
d_v	$N*s/m^2$	Dynamic viscosity of air	1.81E-5
ρ_{air}	kg/m^3	Density of air at sea level	1.23
k	J/K	Boltzmann's constant	1.38E-23
T	K	Absolute Temperature (65°F)	292
λ_{air}	cm	Mean free path of air	3.40E-6
$A_{Facility}$	m^2	Cross-sectional area of facility	100
U_{avg}	m/s	Mean air flow speed	2.56E-3
Re	Unitless	Reynold's number	1,714
τ	$kg/(m*s)$	Shear Stress	3.73E-8
u*	m/s	Friction velocity	1.74E-4
r^+	Unitless	R-value	1.11E-4
C_c	Unitless	Cunningham correction factor	1.01
S_c	Unitless	Schmidt's Number	1.19E+7
v_{vs}	m/s	Settling velocity on vertical surface	9.41E-11
V_{loss}	m^3/s	Rate of viral removal from the air	0.334

Supplemental Figure 1. Spearman's Rho Correlation Coefficients.



Supplemental Figure 1. Spearman's rho correlation coefficients were calculated to assess the accumulation of variability throughout 10,000 model simulations. The parameters associated with an increased risk of SARS-CoV-2 infection include viral shedding per hour, viral concentration in saliva, cough frequency, inhalation rate, and the volume fraction associated with a coughing event. Parameters associated with a decreased risk of SARS-CoV-2 infection included air exchange rates, as well as source and susceptible wearing of face masks. It is important to note that the variability attributed to some intervention parameters were could not be assessed due to their assigned point distributions which had no variability across model simulations.

Supplemental Table 2. Results of Sensitivity Analyses

Modeled Parameter	Spearman's Rho Statistic	Variability Ratio
Viral Shedding per Hour	0.849	5.580
Salivary Virus Concentration	0.760	1.090
Cough Frequency	0.302	1.105
Inhalation Rate	0.157	1.310
100-750µm Diameter Volume Fraction	0.111	1.442
50-60µm Diameter Volume Fraction	0.013	1.178
Hand to Glove Viral Transfer	0.011	1.946
Fomite to Hand Viral Transfer (High RH)	0.010	1.845
Hand to Face Viral Transfer	-0.003	1.604
Viral Decay on Hands	-0.003	1.215
60-100µm Diameter Volume Fraction	-0.004	1.575
Fomite to Hand Viral Transfer (Low RH)	-0.010	1.886
Air Exchange Rate	-0.147	1.318
Source Cloth Mask Protection	-0.162	1.317
Susceptible Cloth Mask Protection	-0.424	1.636
Cumulative Risk of Infection after 12 Hours	N/A[a]	7.616

[a] Rho statistic not available, as correlational analysis was conducted in association with this variable