Developing contingency plans to protect vital sectors in extreme pandemics

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Abstract

Mass labor shortages in an extreme pandemic could pose a significant risk to the continuity of the most vital sectors within critical infrastructure, severely restricting the ability of countries to provide food, water, and other basic needs to their populations. In this study, we investigate vital sector preparedness by using Monte Carlo simulations to estimate the availability of and demand for pandemic-proof personal protective equipment (PPE), reviewing literature on vulnerabilities and response plans, and interviewing experts. The supply of rapidly-mobilizable PPE in the United States was found to be insufficient, with estimated vital sector demand for sufficiently-protective respirators far exceeding stockpiles. This is expected to be the case for most other countries, given that most respirators are produced in China and the US and shortages of more commonplace disposable respirators were already observed globally during COVID-19. Key risk-areas were found for individual sectors, such as high-transmission environments in food processing, and between sectors, such as interdependencies that could lead to cascading infrastructure failures. To enhance contingency planning, we propose five priority measures to protect vital workers if countries are underprepared when an extreme pandemic occurs: (i) mobilize unused private-sector PPE, (ii) improve adaptations to workplaces (e.g., air quality) and work processes (e.g., shift schedules), (iii) establish plans for safe on-site worker housing (iv) address socioeconomic vulnerabilities, and (v) develop back-up plans for meeting basic needs in the event of infrastructure collapse. This research underscores the urgent need for future research and policy efforts to increase pandemic preparedness in vital sectors and provides actionable recommendations to begin doing so.

Keywords

Pandemic; global catastrophic biological risk; existential risk; biosecurity; food security; infrastructure collapse; critical infrastructure

Highlights

- Extreme pandemics could cause mass labor shortages, threatening cascading failures in the vital sectors which provide food, water, and other basic needs to the public.
- In an extreme pandemic, the availability of rapidly-accessible personal protective equipment would fall far short of vital worker requirements.
- Ensuring contingency plans account for mitigating such labor shortages could help maintain food security and meet other basic needs.
- Rapidly ramping up indoor air quality interventions such as germicidal UV, filtration, and ventilation in a crisis could improve safety in vital workplaces.
- Making plans to safely house key workers on-site may provide an additional failsafe in keeping vital services operational.

1. Introduction

Severe worker shortages in a catastrophic pandemic — whether from illness, quarantine, caring for those who are ill, or fear of infection — pose the risk of blocking vital industries from operating and providing basic needs to the public [1]. People cannot survive without food and water, so ensuring their continuity both directly, via the industries themselves, and indirectly, via supporting sectors such as energy, communications, and personal protective equipment (PPE) manufacturing, should be a critical priority. Staff shortages impacted operations during the COVID-19 pandemic throughout the food-water-energy nexus [2–4], despite a reproduction number approximately a fifth of measles [5] and fatality rates an order of magnitude less than other viral epidemics such as Middle East respiratory syndrome coronavirus and Ebola [6].

While these disruptions were managed, future pandemics could be far more severe in their downstream effects. During the 2014–2016 Ebola outbreak in West Africa, rice yields dropped by 12% nationally in Liberia, and by up to 25% in the worst-affected districts, largely driven by fears of infection [7]. This was a situation with an extremely high case-fatality rate, but low prevalence in comparison to COVID-19 and Influenza outbreaks. Absenteeism from a novel pandemic caused by a virus with both extremely high mortality and extremely high transmissibility (i.e., an extreme pandemic) could therefore be catastrophic in its effects on maintaining labor-intensive aspects of vital industries.

PPE provides a key layer of protection [8], yet a future pandemic caused by a virus more transmissible than COVID-19 could render many forms of PPE ineffective at preventing infection. Recent analysis indicates disposable N95 filtering facepiece respirators (FFRs) respirators would be insufficient to keep indoor workers safe from infection in a pandemic as transmissible as measles and as deadly as the 1918 pandemic influenza virus. Instead, workers would require more protective options — referred to as pandemic-proof PPE — such as elastomeric respirators (elastomerics), powered air-purifying respirators (PAPRs), or next-generation products [9]. This scenario would be disastrous, but should not be considered an upper bound. H5N1 Influenza has an average case fatality rate of ~50%, and has garnered recent concern over the potential of a pandemic should it develop efficient human-to-human transmissibility [10,11]. Risk assessment should not be limited to naturally occurring pandemics, either. The CDC lists Nipah virus and Hantavirus under its Category C Bioterrorism agents specifically because of their high case fatality rates and the potential for catastrophic consequences if pathogen engineering were to enable mass transmission [12]. Given that stockpiles and global manufacturing capabilities would likely be unable to produce enough PPE to cover vital sectors in such a scenario [9], there is a need for improved measures to protect these workers.

A combination of lessons learned from the recent pandemic and forward thinking have helped accelerate a number of pandemic preparedness initiatives that are crucial to the future security of vital infrastructure. Strengthening food system supply chains [4], proposing a Global Supply Chain and Logistics Network to improve access to pandemic-related health products [13], proposing a WHO Pathogen Access and Benefit-Sharing System [13], increasing surge capacity in the health workforce [14], developing and stockpiling next-generation PPE [9], advancing the state of germicidal ultraviolet light (GUV) interventions [15–17], promoting globally-coordinated pathogen-agnostic early detection systems [18], and implementing nucleic acid synthesis screening [19] are a few of the highly valuable areas of work within this space to build a world resilient to extreme pandemics.

However, if the world is not prepared when the next pandemic arrives, there need to be contingency plans in place to keep vital services functioning.

Supplementing existing work with response plans for extreme scenarios presents a low-hanging fruit for increasing pandemic resilience. In comparison to many other biosecurity interventions which require significant resources and investment, response plans come with minimal burdens attached. Integrating extreme scenarios into existing government and industry contingency plans may therefore be an appealing option — up-front costs are low when recommendations only need to be rolled out if a crisis occurs. As a first step, this requires profiling the risk area, and identifying the research gaps required to provide actionable recommendations.

In this study, we quantify pandemic-proof PPE availability and requirements, identify vulnerabilities within vital sectors, analyze the requirements of response planning for extreme pandemics, and describe a plan of action to improve preparedness and ensure this research is translated into policy insights. We focus on the sectors required to support food and water security, while encouraging future work on other vital sectors such as healthcare and upstream supply chain inputs. We explore different adaptations to keep industry functioning where protective technology such as PPE is insufficient, and to meet basic needs in the event of localized or widespread infrastructure collapse. In doing so, we aim to provide a novel framework of pandemic resilience measures for vital sectors, focusing on multiple layers of protection to protect populations in the most severe pandemics.

2. Methods

In order to evaluate the preparedness of vital sectors, we first compared the availability of pandemic-proof PPE (Section 2.1) to the requirements of vital workers (Section 2.2). Vital workers were defined as the minimum "workers who are necessary for the basic functioning of society and who likely cannot complete their work from home" [9]. Monte Carlo simulations were used for analysis to manage uncertainties, with key estimates defined as distributions between 90% confidence interval (CI) bounds. The analysis is available online as a Guesstimate model (see Data Availability Statement), and allows a user to change input parameters to reflect different assumptions. After this, we surveyed the literature and interviewed experts (Section 2.3) to analyze vulnerabilities and interventions for catastrophic pandemic scenarios.

We focused on the first three months of a future pandemic. This period of time was chosen as a crisis-buffer to weather the immediate stage of the pandemic and allow for ramp-up of response measures such as increased PPE production to help re-introduce additional essential services that may not be feasible in the short term (e.g., upstream supply chain inputs).

2.1 Pandemic-proof PPE availability

The core logic and assumptions used to estimate rapidly-accessible PPE availability are summarized below (Table 1). Rapidly-accessible PPE was defined as pandemic-proof PPE that could feasibly be distributed to vital workers quickly enough to prevent industry collapse. We focused on respirators due to previous work highlighting larger supply challenges for them than barrier PPE [9], however workers would be expected to also require barrier protection covering their skin and eyes such as hazmat suits and goggles. In brief, we considered national stockpiles, military stockpiles, local healthcare stockpiles, manufacturing and retail inventory, and PPE distributed throughout the private sector. Other sources were excluded due to not meeting the *rapidly-accessible* requirement (e.g., respirators owned by individuals) or being assumed to only contribute a small amount of usable respirators (e.g., non-healthcare public sector organizations).

Table 1. Summary of sources and methods for estimating availability of rapidly-accessible pandemic-proof respirators.

Category	Type	Data source	Extrapolation and Assumptions
National Stockpiles	Elastomerics	SNS purchase exploring national elastomeric deployment strategy [20]	● Stockpile numbers multiplied by normal distr. of 0.5–2
	PAPRs	Federal Coronavirus purchase contracts	● Normal distr. of 25–50% of purchases categorized as national stockpile, based on proportion purchased by HHS ● Result multiplied by normal distr. of 0.5–2
Military Stockpiles	CBRN	Reported total fielded JSGPM masks [21] and annual budgets [22]	● Estimated as lognormal distribution between one year's purchase and all fielded masks
Local Stockpiles	Elastomerics	Survey of healthcare PPE availability [23]	● Normal distr. of 6–12% of hospitals stockpiled multiplied by normal distr. of 50–100% of pandemic requirements
	PAPRs	Survey of healthcare PPE availability [24]	● Estimated as a normal distr. between lower bound of PAPR availability and upper bound of annual purchases in survey
Inventory	Elastomerics	Market data for other types of PPE [25,26]	● Estimated as normal distr. of 17–33% of N95 FFR sales ● Resulting revenue dividing by unit cost ● Lognormal distr. of 50–75% with suitable filters ● Normal distr. of 30–80 days on-hand
	PAPRs	Market revenue reports [27,28]	● Estimated by dividing revenue by unit cost ● Normal distr. of 70–100% suitable ● Normal distr. of 30–80 days on-hand
Private Sector	Elastomerics	Survey of private-sector PPE usage [29]	● Estimated by extrapolating elastomeric-using employees from organization data ● Normal distr. of 58–99% employees use elastomerics in elastomeric-using organizations (based on survey data) ● Lognormal distr. of 1–4 respirators per employee
	PAPRs	Survey of private-sector PPE usage [29]	● Estimated from number of PAPR-using employees in survey ● Lognormal distr. of 0.25–1 PAPRs per employee

PAPR = powered air purifying respirator, CBRN = chemical, biological, radiological, and nuclear hazard respirators, PPE = personal protective equipment, JSGPM = Joint Service General Purpose Mask, SNS = US Strategic National Stockpile, distr. = distribution, HHS = US Department of Health & Human Services, PPE = personal protective equipment. FFR= filtering facepiece respirator

2.1.1 National stockpiles

Elastomerics. The Strategic National Stockpile (SNS) purchased 375,000 elastomeric half-mask respirators (EHMR) in 2021 and distributed 96,000 of them[1] as part of a federal register notice soliciting feedback on a potential EHMR deployment program [20]. It was assumed that the remaining ~279,000 units were stockpiled and represented a significant

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purchase assessing the implementation of an EHMR strategy. As such, 90% confidence intervals of current stockpiles were estimated as a normal distribution of 0.5–2x the ~279,000 figure.

PAPRs. Numbers of stockpiled PAPRs were estimated by first examining federal Coronavirus purchase contracts for the search terms “PAPR” (n=53) or “CAPR”[2] (n=26), and manually filtering for relevance. As with elastomerics, a normal distribution of 0.5–2x this amount was made to estimate confidence intervals of total current stockpiled values. Purchase costs were converted to respirators by dividing by the unit cost of a PAPR, estimated as $1000–2000 [31,32]. Half (51%) of these purchases were made by the Department of Health and Human Services (HHS) under which the SNS falls, so 25-50% of these were categorized as national stockpile purchases.

2.1.2 Military stockpiles

Chemical, biological, radiological, and nuclear hazard respirators (CBRNs). As of 2023, 1.7 million US Joint Service General Purpose (JSGPM) masks had been fielded [21]. Searching unclassified military budgets for all versions of the respirator (M50, M51, and M53) revealed annual purchases of ~100,000–200,000 units from 2011–2018 (which dropped to ~2000–4000 in subsequent years). From these numbers, it was assumed that at least one large year’s purchase would still be available, and up to all the fielded masks would be available. The former scenario seemed more likely, given that the respirators may be lost, sold, expired, used elsewhere by soldiers in combat, or otherwise unavailable, so the 90% confidence interval was defined as a lognormal distribution between these two numbers (150,000–1,700,000).

2.1.3 Local stockpiles

Elastomerics. In a 2015 survey of healthcare facility decision-makers (n=289), 6% of respondents reported elastomerics to be stockpiled, as compared to 67% for N95 FFRs and 24% for PAPRs [23]. As half of the respondents gave an unsure/no answer for elastomerics, 6–12% of facilities nationwide were estimated to have them stockpiled.

The number of respirators stockpiled per hospital was proxied using amounts recommended for influenza pandemic planning. Baracco et al. [31] estimate a healthcare worker requirement of 10,600 elastomerics per 1 million population, under the assumption that a total of 15% of people become infected and seek care over the course of the pandemic. For the US, the number of respirators required (N_R) can therefore be estimated as

$$(i)\ N_R = \frac{e_{pop} \times p}{1{,}000{,}000}$$

where e_{pop} is elastomerics per 1 million population and p is total population. A previous study estimates that healthcare workers would require 1,000 elastomerics per 50,000 patients [33]. This can be expressed as

$$(ii)\ N_R = \frac{e_{pat} \times (p \times i)}{50{,}000}$$

where e_{pat} is elastomerics per 50,000 patients and i is the fraction of people becoming infected and seeking care.

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[2] Controlled Air Purifying Respirator (CAPR) was included to account for the popular “MAXAIR CAPR Helmet” product [30].

Using the US population of 333 million, this implies a national requirement of 999,000 (equation (ii)) to 3,500,000 (equation (i)). Facilities were assumed to be stocked at 50–100% of estimated requirements.

PAPRs. A 2012 survey of 1,066 US acute care hospitals estimated 74,000 (95% CI: 66,000–83,000) PAPRs were on hand nationally, with 210,000 (95% CI: 115,000–313,000) purchased from 2011–2012 [24]. While the numbers of respirators on hand were smaller than those purchased, in an extreme pandemic people may work harder to locate all available units. As such, a normal distribution between the lower limit of stock on hand and the upper limit of purchases was used to estimate total local stockpiled PAPRs.

2.1.4 Manufacturing and retail inventory

Specific data on PPE production is kept confidential [34], so approximate estimates were made based on market reports.

PAPRs. Market reports estimate revenue for PAPRs in the US as 110–770 million [27,28], therefore a normal distribution between these values was used for US PAPR revenue. Using a unit cost of $1,000–2,000 [31,32], and assuming 70-100% are suitable for use, this implies an annual production of ~260,000 suitable units[3]. Assuming 30–80 days of stock on hand in manufacturers and retailers [35], this suggests there are ~40 thousand PAPRs in inventory.

Elastomerics. Neither production data nor market reports are available for elastomerics, but estimates can be made by tethering to similar PPE markets. Outside of pandemics, the US N95 FFR market is “on the order of about $500 million of sales per year” [26]. Market reports suggest that disposable products (e.g., N95 FFRs and surgical masks) make up three quarters of all non-powered respirator revenue, outweighing reusable respirators 3:1 [25]. This was taken as an upper bound of the ratio of N95 FFRs to elastomeric sales, with 6:1 taken as a lower bound since many sales may come from masks other than N95 FFRs. Assuming a unit cost of $25–50 [31], 50-75% have suitable filters, and 30–80 days of stock on hand in manufacturers and retailers [35], this suggests there are ~650 thousand elastomerics in inventory.

2.1.5 All distributed pandemic-proof PPE

All distributed PPE was calculated by adding estimates of available private-sector PPE to the previously calculated figures. Private-sector PAPRs were estimated by multiplying the number of private-sector PAPR-using employees [29] by a lognormal distribution of 0.25 to 1 PAPRs per employee, giving ~160 thousand units. Employee data for elastomerics was not directly available, so this was estimated by multiplying the number of employees who use non-powered PPE by the subset of organizations that use elastomerics, then adjusting the result down to account for 58–99% of employees actually using the PPE [29]. The resulting estimate for employees was multiplied by a lognormal distribution of 1–4 elastomerics per employee, giving ~4.8 million units.

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[3] This appears to align when cross-referenced with the published estimate of 115,000–313,000 PAPRs being purchased by all US acute care hospitals in the 2011–2012 year [24].

2.2 Estimating pandemic-proof PPE requirements

2.2.1 All vital workers

Existing estimates were used to inform a range of realistic potential values for the size for the vital workforce; however, creating a detailed profile is outside the scope of this paper. McNicholas and Poydock [36] estimated the number of US essential workers as 55 million, defined by executive orders during COVID-19. As the number of vital workers will be lower than this, it provides a real-world data point to start from.

The upper bound of vital workers was informed by Blueprint Biosecurity and Gryphon Scientific [9], who estimated vital workers for societal function in future pandemics by assessing individual job categories within critical infrastructure. This resulted in the inclusion of all agriculture and healthcare workers, 39.1% of industry workers, 38.4% of service workers, and 40% of military workers. For the US, which has 11 million essential agriculture workers, 17 million essential healthcare workers [36], 22 million non-food industry workers [37], 18 million non-food service workers [38], and 2.86 million military workers [39], this sums to approximately 45 million, or 82% of essential workers (Table 2).

Table 2. Summary of sources and methods for estimating pandemic-proof respirators required to support production of more respirators.

Category	Sub-category	Data Source	Extrapolation and Assumptions
All vital workers	Total workers	Previous estimates of essential [36] and vital [9,40] workers.	● Vital workers estimated as normal distr. of 25–82% of 55 million essential workers ● Normal distr. of 70–100% of workers require pandemic-proof PPE ● Lognormal distr. of 1–2 respirators per worker
PPE production	PPE workers	US PPE workforce [41]	● All 17,000 workers required
	Distribution workers	USPS workforce [42,43] and pre-COVID-19 N95 FFR production [26]	● Lognormal distr. of 5–20% of USPS workers required ● 67% are mail carriers and can use N95 FFRs ● 33% are warehouse/office workers and require pandemic-proof PPE
	Telecoms.	US telecoms. workforce [44]	● Lognormal distr. of 5–20% of 250,000 telecommunications workers required ● 50% require pandemic-proof PPE ● 50% can use N95 FFRs
	Energy sector	Data on energy requirements of PPE production, distribution, and telecommunications.	● Estimated energy requirements make up <1% of total consumption ● Network effects may increase worker requirements ● Lognormal distr. of 1–10% of energy workers required

PPE = personal protective equipment, distr. = distribution, USPS = United States Postal Service, FFR= filtering facepiece respirator, telecoms. = telecommunications.

The lower bound estimate for vital workers was informed by the framework proposed by Gopal et al. [40], breaking down essential workers into primary, secondary, and lifesaving workers. Primary workers cover the provision of food, water, energy, communications, PPE, and law enforcement. For food and agriculture, in a minimal viable sector it was assumed that restaurants and retailers would be closed and food would be delivered to people. Therefore, all services, stores, and textile workers were removed to leave 5.7 million workers [45]. All 0.11 million essential water workers were retained. Given commercial needs would be much lower, half of essential energy and telecommunications workers were kept — 0.66 million and 1.6 million, respectively [36]. All 17 thousand current PPE workers were kept to cover PPE manufacturing [41], and a reduced 20% of military workers were selected for law enforcement (0.57 million) [39]. For secondary workers, 20% of essential transportation, warehousing, and delivery workers (0.79 million); 20% of essential chemical sector workers (54 thousand), 10% of essential industrial, commercial, residential facilities and services workers (0.68 million); and 10% of essential critical manufacturing workers outside of direct PPE production (0.18 million) were assumed to be required to ensure delivery of basic needs. Finally, for lifesaving workers, 20% of healthcare (3.3 million) and emergency services (0.37 million) were assumed to be the minimum required to respond to an extreme pandemic. This was based on data showing similar percentages of healthcare workers (~24%) being directly involved in the COVID-19 response [46]. For this lower bound, it was assumed all non-urgent in-person healthcare would be postponed and telehealth would be maximized wherever possible. These reduced sector figures sum to approximately 14 million, or 25% of essential workers.

Given the proportions suggested by these existing definitions, vital workers were therefore estimated as 25–82% of the essential workforce. Workers who work outdoors or alone may be protected by N95 FFRs, with all other workers requiring more protective options such as elastomerics or PAPRs [9]. However, due to concerns that fit failure may reduce effectiveness of all PPE, 70–100% of vital workers were assumed to require elastomerics or PAPRs. As reusable respirators may still occasionally need to be replaced, a lognormal distribution of 1–2 units per worker was assumed.

2.2.2 Requirements for PPE production alone

Manufacturing and distribution workers would be required to directly support PPE production in an extreme pandemic. There are an estimated 17,000 PPE workers in the US [41], and all of these were assumed to be vital and in need of PPE. For distribution, the US postal service (USPS) delivers 24 million packages daily [43], whereas pre-COVID production of N95 FFRs was ~1.3 million per day [26]. Taking a conservative assumption of one respirator per package makes up ~5% of daily deliveries (this is overly conservative but provides leeway for other delivery requirements in the supply chain). Therefore, a lognormal distribution of 5–20% was assumed to cover requirements, given distribution is likely to scale down worse than linearly. As 330k [42] of USPS's 500k workers [43] are mail carriers, these 67% of workers were considered to be protected by N95 FFRs. The remaining 33% were assumed to require more protective PPE due to higher infection risks of warehousing/office work.

Workers from the telecommunications and energy sectors would be required to indirectly support PPE production in an extreme pandemic. While PPE production may not make up a large proportion of telecommunications, network effects may require a relatively large portion of communication systems to stay operational. Therefore, a lognormal distribution of 5–20% of the 250,000 US telecommunications workers were assumed to be needed, with half of workers requiring pandemic-proof PPE given most workers are involved in installation and repairs which is likely to be low-contact [44]. Energy requirements were calculated by estimating requirements for each of the vital industries, dividing this by total US energy consumption, and multiplying by total US energy workers. Workers in electric power generation; transmission, distribution, and storage; and fuels were included while those in energy efficiency and motor vehicles were excluded. This suggested energy requirements that were approximately half a percent of total consumption. Due to potential network effects increasing worker requirements, a lognormal distribution of 1–10% of energy workers was taken.

2.3 Profiling vital industry preparedness for extreme pandemics

2.3.1 Review of peer-reviewed literature, industry documentation, and media

A narrative literature review was conducted for each selected vital industry using academic literature databases, search engines, and targeted organization searches. In order to adequately assess the workforce needed to maintain food and water security, we focused on the sectors which directly provide these services (food and water) and those which indirectly support them (energy, telecommunications, and PPE manufacturing). With [vital industry] as a placeholder for variations of food, water, energy, PPE, or (tele)communications, key search terms included (COVID-19 OR pandemic) response plans [vital industry], (COVID-19 OR pandemic) preparedness [vital industry], (COVID-19 OR pandemic) adjustments [vital industry], (COVID-19 OR pandemic) operations [vital industry]. Academic literature was included for robustness of sources, whereas non-academic sources were included due to the wealth of information in industry and government documentation. Targeted organization searches were used to find key information on operations after identifying the major organizations within an industry.

2.3.2 Key informants

Key informants (n=8) were interviewed to gain additional insights for this study and provide sense-checks for researcher findings and theories of pandemic preparedness. These contacts were made up of workers with operations management experience in vital industries (n=4), academics specializing in vital industries (n=3), and one specialist worker from a non-governmental organization (n=1).

Interviews were conducted in 30–60 minute slots via video call (n=6), phone call (n=1), or email correspondence (n=1). A semi-structured interview format was used, composed of a core list of compulsory questions (~20 minutes), an optional list of clarifying questions, and follow-up questions asked based on interviewee responses[4].

2.3.3 Evaluation of vulnerabilities and recommendations

Research findings from the literature review, interviews, and PPE analysis were synthesized to identify key vulnerabilities throughout vital sectors, recommendations for response plans, and areas for future work. An evaluation framework was developed to aid in comparing the value of adaptations in an extreme pandemic (Figure 1). This framework consisted of six criteria: (1) speed of deployment, (2) feasibility/scalability, (3) additional cost, (4) effectiveness (of maintaining industry function), (5) likelihood of effectiveness, and (6) adherence. Results were compared and cross-evaluated in an internal interactive scenario-planning workshop to facilitate discussion around different rankings.

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[4] Interview questions available on request.

Intervention	Score	Definition	General Considerations (not ordered)
Speed of Deployment	1	Industry is at risk of collapse before intervention is deployed (deployment > 4 weeks after identification)	How quickly was this done in covid? How quickly could it theoretically be done providing more advance planning?
	2	Large staff shortages are likely before deployment (deployment <= 4 weeks after identification)	
	3	Moderate staff shortages are likely before deployment (deployment <= 2 weeks after identification)	
	4	Intervention is likely to be deployed before signficant drop in vital workers (deployment <= 1 week after identification)	
	5	Intervention can be deployed at scale immediately (deployment < 24 hours after identification)	
Feasibility/ Scalability	1	There are numerous significant barriers to scaling up the intervention, including substantial technological and/or logistical challenges.	Are there significant barriers to scaling this intervention? Technological barriers? Logistical barriers? If there are barriers to effectively rolling out an intervention, how difficult are these to solve? Does the adaptation hit diminishing returns, or stop being as effective as it is being scaled? Does applying this adaptation (at scale) trade off against key work that needs to be done?
	2	There are multiple notable barriers to scaling, with technological and/or logistical issues presenting considerable challenges.	
	3	There are some barriers to scaling, including manageable technological and logistical challenges that may require substantial effort and resources.	
	4	There are few barriers to scaling, with minimal technological and/or logistical challenges.	
	5	There are virtually no significant barriers to scaling the intervention.	
Additional Cost	1	Cost is so expensive it is expected to render the intervention ineffective (will not happen).	How likely is the cost of this intervention to be a barrier to its implementation and deployment at scale? (Consider that in some cases it may replace something else which also has a cost associated with it.) What are the financial costs? What is the administrative burden (cost of additional time staff spend on this)?
	2	Cost is expected to signficantly reduce implementation and/or scale of the intervention.	
	3	Cost is expected to moderately reduce implementation and/or scale of the intervention.	
	4	Cost is expected to be a minimal barrier to implementation and/or scale of the intervention.	
	5	Cost is not expected to impact implementation and/or scale of the intervention.	
Effectiveness	1	This intervention is expected to have no impact on maintaining industry.	If it works as intended, what impact could this intervention have on reducing the risk of industry collapse?
	2	This intervention is expected to have a small impact on maintaing industry.	
	3	This intervention may somewhat help preserve industry.	
	4	This intervention is likely to be effective in maintaining industry.	
	5	This intervention is likely to be extremely effective in maintaining industry. Maintaining industry without this intervention seems unlikely.	
Likelihood of Effectiveness	1	The intervention has minimal to no evidence supporting its effectiveness, or there are signficant uncertainties that are highly unlikely to be resolved in the short term.	Are there major uncertainties regarding this intervention's effectiveness? If effectiveness is uncertain, are large amounts of work needed to resolve these uncertainties? Will this intervention only be effective in certain situations, or for certain types of pandemic?
	2	There is limited evidence suggesting the intervention might work. Resolving unceraintties in the short term could be feasible, but appears unlikely.	
	3	There is some evidence suggesting the intervention might work. Resolving uncertainties in the short term would likely take a moderate amount of effort.	
	4	Strong evidence supports the intervention's effectiveness.	
	5	The intervention is backed by robust and consistent evidence demonstrating high effectiveness.	
Adherence	1	Nonadherence is likely to render the intervention ineffective.	How likely are vital workers to adhere to this intervention? Consider: Ease of doing it wrong? Inconvenience/discomfort? Worker concerns about loss of autonomy? What was adherence in previous pandemics or other catastrophes?
	2	Nonadherence is likely to significantly reduce effectiveness.	
	3	Nonadherence may somewhat reduce effectiveness.	
	4	Nonadherence is unlikely to impact effectiveness.	
	5	Nonadherence is extremely unlikely to impact effectiveness.	

Figure 1. Evaluation framework criteria.

3. Results

3.1 Pandemic-proof PPE Estimates and Sector Vulnerabilities

Pandemic-proof PPE availability was estimated to be sufficient to support the production of more PPE, but far below the amount required to protect all vital workers for the first three months of an extreme pandemic (Figure 2). PPE production would require 270 thousand (90% CI: 110–660 thousand) units of pandemic-proof PPE, which could potentially be covered by national stockpiles which total 440 thousand (90% CI: 210–670 thousand) units. In contrast, all 27 million (90% CI: 14–48 million) vital workers were estimated to require 33 million (90% CI: 16–65 million) units, far exceeding combined hospital, military, and national stockpiles ("all stockpiles") of 1.5 million (90% CI: 0.86–2.7 million) units. Adding all manufacturer, retailer, and private workplace stock to stockpiles (“all rapidly-accessible PPE”) would still be insufficient at 7.1 million (4.2–12 million) units.

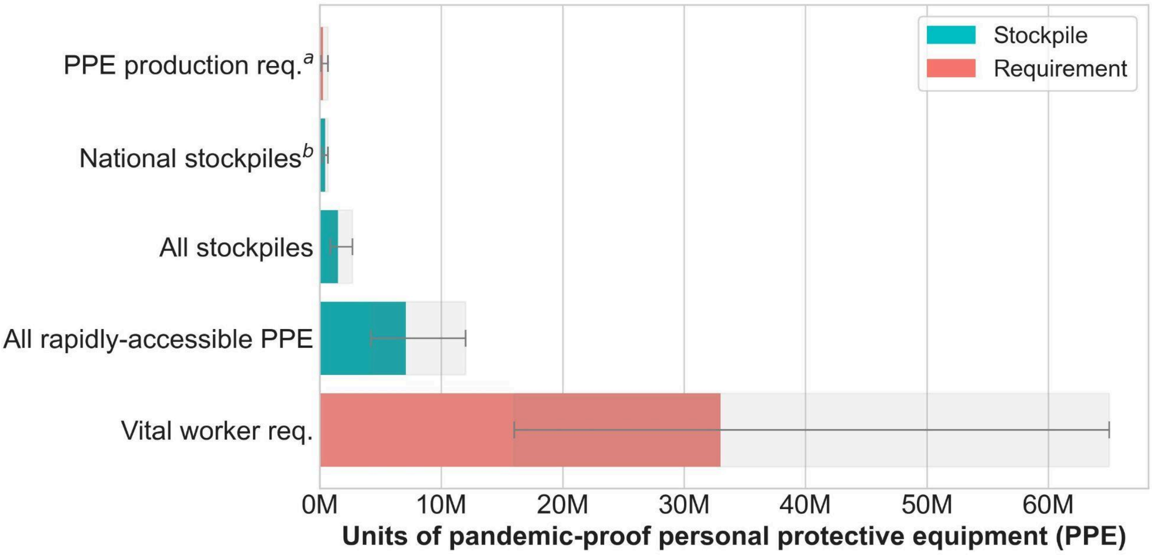

Figure 2: Comparison of PPE stockpiles and PPE needed in an extreme pandemic. PPE = personal protective equipment, [a]Excluding law enforcement requirements, [b]Excluding military stockpiles, req. = requirement.

PPE manufacturing was deemed relatively more resilient than other sectors, given staff can be equipped with respirators produced in-house. However, PPE provides only one layer of defence, and it is important that response plans ensure existing and repurposed PPE manufacturing facilities have a portfolio of protective measures in place.

3.2 Food Sector Vulnerabilities

Within the food sector, key transmission vulnerabilities were identified from farm to fork. Labor shortages of 1.9% were observed nationwide during COVID-19 in the US, alongside a 2.6% decrease in agricultural production in 2020 [47]. Ebola-induced labor shortages in less-industrialized West African countries were associated with significantly worse impacts — rice yield shocks of 12% nationally and 25% in the worst-affected districts [7] — suggesting a catastrophic pandemic could result in even greater losses. US food processing was hit hardest during COVID-19, with a peak 40% drop in meat processing [48]. Workers operate in high-density plants where social distancing is impractical [49] and loud conditions facilitate increased emissions due to shouting [50]. While transportation roles, in contrast, can be lower-contact, the reliance of most regions on distant food sources [51] renders them entirely dependent on specialized transport workers who are difficult to replace [52].

Addressing this risk requires an understanding of farm worker vulnerability. Racial and ethnic minority food workers experienced a disproportionately high burden of COVID-19 infections and make up half of the agricultural workforce [49]. Moreover, undocumented farm laborers lack protection from the government despite making up 41% of the crop agriculture farm workforce [53]. Workers often share modes of travel, increasing the risk of infections spreading through teams, and are often not granted paid sick leave or health insurance coverage, disincentivizing isolation when infected [50]. Working in a low-contact environment cannot keep vital workers safe if they get infected outside of work, and improved planning will have to account for this.

3.3 Water Sector Vulnerabilities

During COVID-19, a third of US water utilities experienced staffing shortages and impacts on operations, exacerbated by 40% experiencing hiring difficulties [2]. Staff shortages could instigate a number of failure points in future crises, from having insufficient workers to maintain supply, monitor and treat water, repair mains and pump systems, or keep payroll systems functioning to incentivize employees and vendors to keep working in a crisis [54]. Operators, technicians, and drivers were identified as specific vulnerabilities due to criticality for continuity of operations [55] and difficulty in hiring [2], suggesting these may also be bottlenecks in future pandemics.

Examining water access also highlights the interdependence of vital sectors in maintaining and protecting the workforce in a future pandemic. Utility disconnections make it harder to stay at home, follow social distancing orders, and follow hygiene requirements such as hand-washing. A national moratorium on water shutoffs could have reportedly prevented half a million infections during COVID-19 [56], while full utility disconnection bans could have reportedly reduced infections by 9% and deaths by 15% [57]. If shutoffs happen in a future pandemic, they could stress vital sectors due to increased infections in the workforce. At a larger scale, disconnections caused by utility failure could trigger a cascading cycle of infrastructure collapse: losing access to water and electricity leads to increased infections, which leads to shocks to the vital labour supply, which leads to higher risks of more utility failures.

3.4 Energy Sector Vulnerabilities

The energy sector has gained resilience through preparedness planning in response to SARS, H1N1, Ebola, Zika, and COVID-19 [58,59], though extreme scenarios may require greater efforts. Mission-critical control room operators and technicians still have to work in close-quarters. A single infection requires quarantine of the entire shift, meaning energy organizations could run out of these workers in a few weeks without sufficient planning [3]. Risks may be higher in areas heavily reliant on nuclear power, such as France where it provides 65% of electricity [60]. Nuclear plants require refueling every 18–24 months, involving hundreds of specialized workers in close proximity—a process challenging to maintain during pandemics [61]. A collapse of the energy sector would induce catastrophic collapse of all other vital sectors, highlighting the need for additional failsafes where vulnerabilities remain.

For locations dependent on other sources of power, supply and demand fluctuations still stress the grid by overloading infrastructure. In particular, this may be exacerbated by inadequate forecasting of drastic changes in usage patterns causing transformer failure [59] and a lack of rationing plans. While gasoline rationing during World War II [62] and rolling blackouts during the 2000–2001 California energy crisis [63] mitigated shortages, not accounting for pandemic-specific rationing plans may be a further cause of sector vulnerability.

3.5 Telecommunications Sector Vulnerabilities

Functioning telecommunications are required to maintain coordination in an extreme pandemic, but labor shortages may threaten this. Maintaining staff critical for operational continuity — operators and technicians, in particular — was an issue for the majority of data centers both before and during COVID-19 [64]. These skilled worker positions are not easily replaceable, and even partial staff absences could cause losses of communication systems. Over 70% of all surveyed data centers outages were related to human error [65], with labor shortages and tiredness leading to more outages and incidents. In order to safeguard against these effects, protecting key positions and cross-training workers on mission-critical tasks will be required in a global catastrophe.

The telecommunications industry plays a critical role in reducing vital worker infections by enabling remote work — a role that may be jeopardized by energy constraints. During COVID-19, quarter 2 of 2020 saw outages caused by lack of power increasing by 69% compared to quarter 2 of 2019 [66]. While the impact of power outages can be mitigated by having back-up generators, this is dependent on both having generators and having fuel to run them. Operators without priority fuel delivery contracts may be unable to secure them post-catastrophe [67], further highlighting insufficient backup power plans as an operational vulnerability that could have large effects on vital worker safety across industries.

3.6 Post-collapse scenarios

As long as vulnerabilities remain within vital sectors, industry collapse remains a threat. Without industrial agriculture, yields of major crops are anticipated to drop 15–37% in the year following a catastrophe [68], before considering any reductions from labor shortages. Moreover, additional effects throughout the food supply chain could trigger famine in the event of a year-long industry loss event, even in countries such as the US with high levels of food production [69]. In response to these downstream threats from industry loss, vulnerabilities and potential solutions were explored.

Food processing, water treatment, and energy prioritization were identified as underexplored areas within post-collapse solutions, presenting vulnerabilities for extreme pandemics. Food processing is energy-intensive [70] and high-contact [49], which suggests it may be a bottleneck in meeting food needs in a post-collapse catastrophe. Additionally, while some people may be able to reach natural water sources if pipes run dry, emergency guidance is lacking on which access options (e.g., water trucking, rainwater collection, groundwater collection via dug wells or springs, surface water) and treatment options (e.g., chlorination, filtration, solar disinfection) are suitable and scalable for different locations. A broader question remains, too, of how limited traditional fuel reserves and alternative fuels should be used, balancing needs of necessities such as food production, distribution, water trucking, and backup generators for PPE manufacturing. Making progress towards solving these uncertainties will add resilience to the current collection of resilience measures against industry collapse.

4. Discussion

4.1 Implications for contingency planning research

Given that vital industries remain vulnerable to extreme scenarios, response plans can serve as a back-up if preparedness measures fail to prevent an outbreak from spreading. Through profiling vulnerabilities and existing response plans within vital sectors, five key areas were identified as priority research and policy recommendations to protect food and water security in an extreme pandemic — (i) allocate PPE, (ii) adapt workplaces, (iii) provide high-quality on-site accommodation, (iv) acknowledge vulnerabilities, and (v) develop collapse back-up plans. These are explored below:

(i) Allocate PPE

The modeling of PPE demand and supply shown in this study suggests rapidly-accessible pandemic-proof PPE is highly unlikely to cover all vital workers, so PPE allocation strategies should be developed to minimize deaths caused by both infections (i.e., direct factors) and loss of basic needs such as food and water (i.e., indirect factors). This will require first creating a detailed profile of vital worker numbers to better understand how many workers need to be protected, and who is most at risk based on previous workplace transmission data. Doing so can help identify high-risk roles such as healthcare and food processing workers that will likely require the most-protective PPE to protect against extreme pathogens (e.g., PAPRs and hazmat suits); medium-risk roles that still require highly-protective PPE (e.g., elastomerics, surgical gowns, and goggles); and lower-risk roles that may be sufficiently protected with more basic PPE (e.g., disposable N95 FFRs and any remaining barrier PPE) if combined with significant workplace adaptations. Linked to this, our analysis suggests there are large volumes of pandemic-proof PPE outside of traditional stockpiles. Figuring out how to efficiently redistribute respirators from non-vital businesses, manufacturing inventory, and retailer inventory to those who need it most has the potential to significantly increase resilience in a future crisis.

(ii) Adapt workplaces

Organizations will need to physically and operationally restructure workplaces to minimize infections and preserve labor supply. In the absence of ubiquitous, robust indoor air quality (IAQ) measures such as Far-UVC [15], response plans should provide guidance on rapidly ramping up alternatives such as upper-room GUV (UR-GUV), in-room filtration, and ventilation. A safe working environment would likely need to aim for at least an order of magnitude greater equivalent clean airflow rate per person than current best-practice systems such as ASHRAE-241, given they are designed around comparatively less-transmissible pathogens such as COVID-19 [71]. Precursor studies should determine how both existing and additional infrastructure could be repurposed to improve IAQ in vital sectors. This could take the form of increasing ventilation rates in existing systems, rapid construction of Corsi-Rosenthal type filtration units [72], massively redistributing fans to increase ventilation, or expanding usage of UR-GUV solutions such as eggcrate-GUV in a crisis [73]. Most importantly, the relative efficacy of these options in reducing transmission should be included in analysis, accounting for combination-use with suboptimal PPE such as disposable N95 FFRs and surgical masks. Such work would inform how much vital worker safety could be improved during PPE shortages.

More general measures should start with best-practices learned from COVID-19, such as maximizing teleworking, implementing reduced shift schedules with no contact between crews, enhancing cleaning protocols [74], creating barriers and increasing distance between workers [50,75], and ranking maintenance needs to determine which processes can be deferred. However, these plans should be built upon with stronger efforts to manage shortages. For example, to manage shortages at the peak of an epidemic, shifting from bringing in new hires to redistributing tasks among existing employees can double labor availability by reducing new infections from outside sources [76]. Additionally, cross-training workers on mission-critical tasks can eliminate singular points of failure [55,77]. Furthermore, all vital sectors should strive to have collaborative response networks in place, such as the Water/Wastewater Agency Response Network (WARN), to loan employees and resources to areas with high absenteeism after quarantine [54]. Enhancing workplace adaptations to better prevent and account for severe shortages is a key recommendation for future pandemics.

Implementing response plans successfully will require strong communication plans combined with robust mental health and social support. Doing so can reduce drivers of absenteeism [78,79], and accounting for cultural and language differences [49] should reduce the chance of miscommunication driving transmission. This became apparent during COVID-19 when the quality of contact tracing was reported as worse for Spanish-speakers in the US, who make up a large fraction of the agricultural workforce [80]. Moreover, strong mental health planning will be critical to ensuring that response plans are adhered to and that laborers feel safe and engaged enough to keep working. This will be particularly relevant to more drastic measures, such as housing workers on-site, and most likely need to be delivered remotely to minimize infection risks.

(iii) Develop plans to provide vital workers with safe on-site accommodation

Without enough pandemic-proof PPE to protect vital workers, an additional line of defense is to offer safe on-site accommodation to protect them from infection. During the COVID-19 pandemic some workers committed to month-long live-ins, staying on-site to keep water treatment [81], the electricity grid [82], and the production of PPE inputs [83] running. Some of these cases saw secondary shift teams quarantining at home before swapping out with the first teams, which could be done between waves of a future pandemic to reduce the strain of isolation on workers. Future research should analyze the prevalence of emergency on-site housing facilities in vital sectors, the capacity of repurposed accommodation such as hotels and trailers, and the potential to rapidly construct additional facilities where required.

However, providing facilities alone is not enough. Migrant agricultural workers suffered from crowded, unsanitary on-site housing; more infections; and higher rates of preventable death throughout the COVID-19 pandemic [84]. In order for on-site housing to actually keep workers safe, country and industry plans will need to encourage participation through generous compensation, put protections in place to prevent exploitation, and set stringent quality standards to avoid infections spreading in employee housing.

(iv) Acknowledge vulnerabilities

The essential workforce is largely made up of lower-income and minority groups [36], who are at higher risk of infection [85], and approximately one tenth are undocumented migrants with even greater risks [86]. Given that vital workers are a subset of essential workers, it is imperative that response plans adequately address these vulnerabilities. One actionable finding is to ban utility disconnections during a future pandemic [57], as they are likely to disproportionately increase infections amongst vulnerable workers who are not staying on-site. Beyond this, response plans should also ensure the provision of safe travel and (on-site) accommodation options for workers to prevent infections outside of the workplace.

(v) Develop collapse back-up plans

Response plans should also include guidance on meeting basic needs in the event of local or widespread infrastructure collapse. As collapse is likely to occur in only the most severe scenarios, even localized loss of basic services poses a significant threat as neighboring regions or countries would likely be too preoccupied in protecting their own populations to provide any humanitarian aid or assistance. While developing PPE, IAQ, on-site housing, and workplace interventions is crucial to improving resilience, each is currently below the high levels of protection needed to ensure vital sectors are protected from future pandemics. Post-collapse solutions should therefore be viewed as another layer of defense against extreme pandemics, providing a safety net should first-line interventions fail to maintain vital industry function (Figure 3).

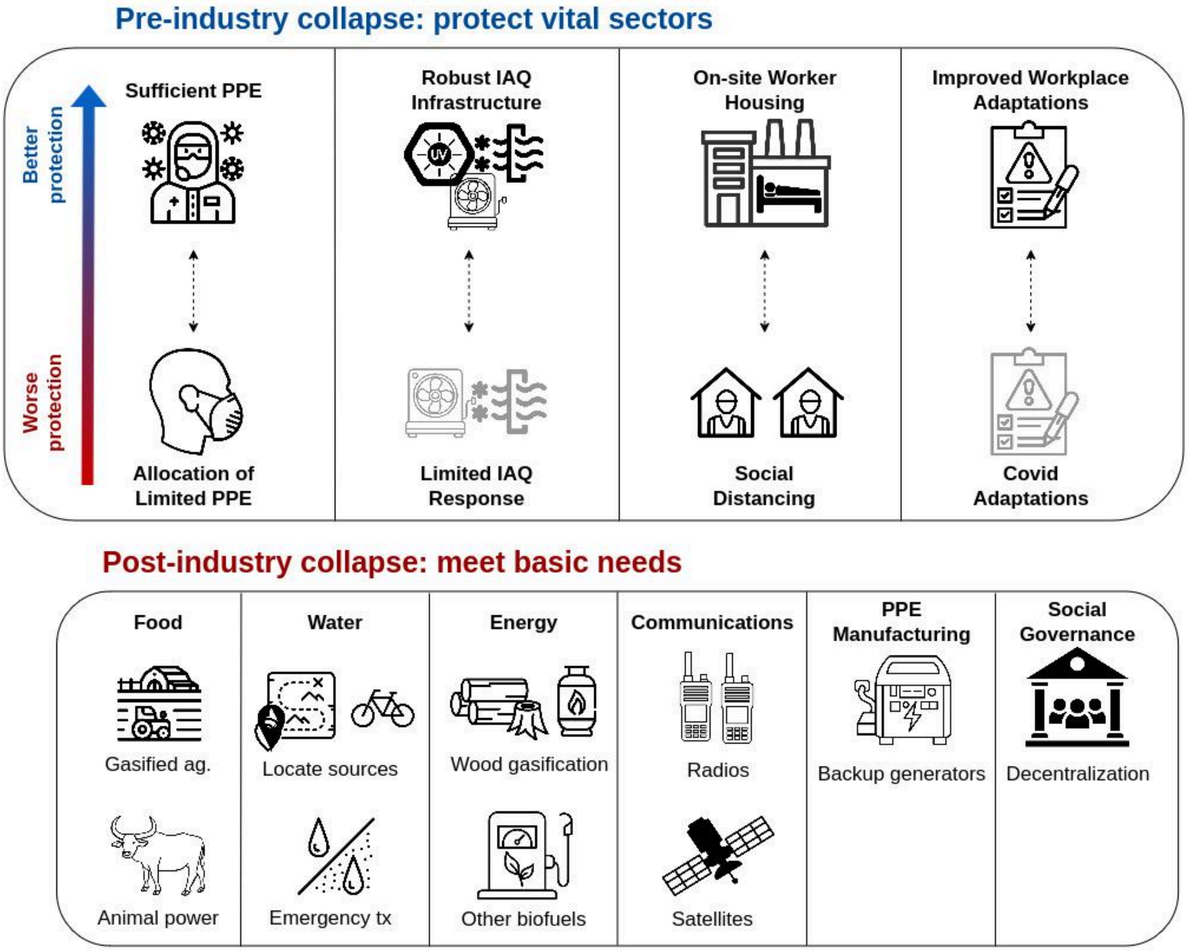

Figure 3: Layers of defense for meeting basic needs in extreme pandemics. PPE = personal protective equipment, IAQ = indoor air quality, gasified = retrofitted to run on wood gas as was done in WWII [87], ag. = agriculture, tx. = treatment.

Existing literature has begun to identify components of this safety net. Wood gasification [87,88] or other biofuels could be used as an energy source, supporting industrial farming, transportation, water trucking, or generators for PPE manufacturing. In the absence of this, animal power and human-powered transport could provide alternative sources of power for agriculture and water distribution [89,90]. Meeting water needs in this manner would also require assessment of the nearest suitable water sources for each population, and assessment of emergency treatment options available for different locations. For telecommunications, satellite phones and backup shortwave radio networks could potentially provide functional alternatives in the event of large-scale electricity loss [91], and for social governance, local community networks could provide a decentralized alternative should traditional governance and law enforcement structures struggle to remain coordinated and functional. However, key questions remain unanswered. Further work should aim to fill gaps in the post-collapse portfolio such as food processing, water treatment, energy prioritization strategies, and decentralized social governance structures.

4.2 An opportunity for strengthening global pandemic resilience

Now is an opportune moment to develop resilience to extreme pandemics, with countries openly considering the reality of more severe crises. The World Health Organisation (WHO) has prioritized preparedness for novel outbreaks disrupting food and water since 2015 [92], and recent discussions of a "Disease X" 20x worse than COVID-19 at the World Economic Forum [93] showcase that global leaders are open to discussing mitigation strategies. Just this year, the White House released a memorandum to investigate resilience requirements in critical infrastructure [94]. While our analysis focused on the US, the findings are broadly applicable — we expect that most other countries would face significant shortages of pandemic-proof PPE in an extreme pandemic given that most respirators are produced in China and the US [9] and shortages of more commonplace disposable respirators were already observed globally during COVID-19 [95–97]. With conversations on severe pandemics taking place at the highest levels, the pandemic treaty negotiations ongoing [98], and COVID-19 disruptions fresh in the minds of operations teams, there is an opportunity to engage key stakeholders across the globe.

In order to ensure research is translated into effective pandemic resilience, we recommend a three-pronged approach with a focus on adapting existing disaster frameworks. Firstly, research findings should be packaged into an additional "vital" extension of existing continuity of operations plans, taking into account the needs of the governments, industry groups, and organizations that would be involved in rolling out these plans in a crisis. Secondly, governments should be advised to take into account extreme pandemic risks and response needs in critical infrastructure contingency plans such as those developed under the EU Directive on the Resilience of Critical Entities [99] and the US National Security Memorandum on Critical Infrastructure Security and Resilience [94]. Thirdly, industry groups should be engaged to provide vital sector organizations with this information, such as via the threat warning and risk mitigation capabilities of Information Sharing and Analysis Centers [100]. In doing so, existing communication networks can be employed to reach as many organizations as possible, maintaining a larger proportion of vital services should a catastrophic pandemic arise.

4.3 Limitations

This work is intended to highlight the underexplored risks of labor shortages on food and water security in future pandemics, and is only an initial analysis of the topic. The scope was mainly constrained to food, water, energy, telecommunications, and PPE manufacturing, which is an oversimplification of true requirements. In particular, distribution, logistics, and healthcare require more attention, as do the practicalities of delivering food to massive numbers of people sheltering in place and providing recommendations for highly varied country contexts. There is also more to be done on the sectors that were covered, such as extraction and refining within the energy industry. Additionally, while a small number of industry stakeholders were interviewed for this study, increasing stakeholder involvement in future work would be significantly useful for making sure findings and recommendations are validated and actionable.

5. Conclusion

This study highlights significant gaps in vital infrastructure pandemic preparedness that could jeopardize the ability to meet basic food and water needs in a catastrophe. Estimated shortages of pandemic-proof PPE are expected to exacerbate existing vulnerabilities in the food, water, energy, communications, and PPE manufacturing sectors, threatening infrastructure collapse. However, targeted research on the topics proposed here can begin to mitigate this risk, and follow-on work from the wider community can greatly further this effort. By engaging researchers, policymakers, and industry leaders in a coordinated effort, we can better safeguard vital services and protect populations from future pandemics.

Acknowledgements

We would like to thank Oxford Biosecurity Group for collaborating with us to run this project and Jesse Smith for his input on indoor air quality interventions.

Funding

This work was supported by the Alliance to Feed the Earth in Disasters (ALLFED).

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Data Availability Statement

The main analysis is available online as a Guesstimate model: https://www.getguesstimate.com/models/23914. Supplemental code is available online at https://github.com/allfed/vital-industry-p4e

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