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Review

Challenges and future opportunities to unlock the critical supply chain of personal and protective equipment (PPE) encompassing decontamination and reuse under emergency use authorization (EUA) conditions during the COVID-19 pandemic: Through a reflective circularity and sustainability lens

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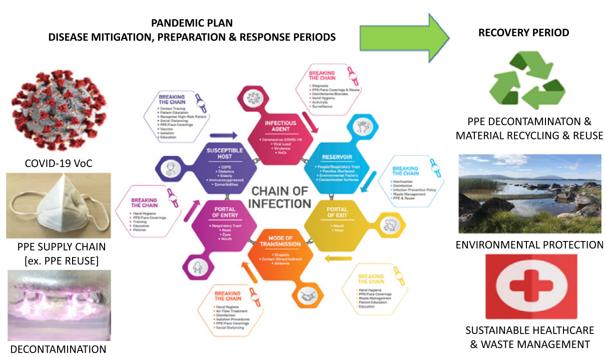
HIGHLIGHTS

- COVID-19 pandemic caused disruption in supply chains to vital PPE
- Lack of knowledge to inform key policies and appropriate disease mitigation strategies globally
- Decontamination technologies may enable safe treatment of PPE waste for recycling and long term sustainability
- Co-circulating COVID-19 variants of concern will continue to challenge our healthcare system
- Emerging opportunities to meet harmonized pandemic responses, circular bioeconomy and green innovations

GRAPHICAL ABSTRACT



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ABSTRACT

Severe acute respiratory syndrome Coronavirus-2 (SARS-CoV-2), and the resulting coronavirus disease (COVID-19), was declared a public health emergency of global concern by the World Health Organization (WHO) in the early months of 2020. There was a marked lack of knowledge to inform national pandemic response plans encompassing appropriate disease mitigation and preparation strategies to constrain and manage COVID-19. For example, the top 16 "most cited" papers published at the start of the pandemic on core knowledge gaps collectively constitute a staggering 29,393 citations. Albeit complex, appropriate decontamination modalities have been reported and developed for safe reuse of personal and protective equipment (PPE) under emergency use authorization (EUA) where critical supply chain shortages occur for healthcare workers (HCWs) caused by the COVID-19 pandemic. Commensurately, these similar methods may provide solutions for the safe decontamination of enormous volumes of PPE waste promoting opportunities in the circular bioeconomy that will also protect our environment, habitats and natural capital. The co-circulation of the highly transmissive mix of COVID-19 variants of concern (VoC) will continue to challenge our embattled healthcare systems globally for many years to come with an emphasis placed on maintaining effective disease mitigation strategies. This viewpoint article addresses the rationale and key developments in this important area since the onset of the COVID-19 pandemic and provides an insight into a variety of potential opportunities to unlock the long-term sustainability of single-use medical devices, including waste management.

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Contents

1. Introduction

Severe acute respiratory syndrome Coronavirus-2 (SARS-CoV-2), and the resulting coronavirus disease (COVID-19), was declared a public health emergency of global concern by the World Health Organization (WHO) in the early months of 2020 (Sohrabi et al., 2020). The occurrence of COVID-19 took the world by surprise (Ahmed et al., 2020; WHO, 2020). In addition to significant loss of life and morbidity, COVID-19 disrupted social daily norms that also impacted world trade (White et al., 2021). COVID-19 is also seen as a rare "black swan" event where there is no playbook to advise on best-practice solutions from prior lessons learnt, including the availability of appropriate countermeasures (Rowan and Galanakis, 2020). The aim of this viewpoint article is to critique the main developments affecting the personal and protective equipment (PPE) supply chain during the COVID-19 pandemic along with embracing emerging trends and opportunities. For example, deficiencies in our ability to maintain a supply chain of single-use PPE for frontline healthcare workers (HCWs) was underappreciated; yet, emphasis is shifting away from the potential reuse of critical PPE under conditions of extreme shortages (emergency use authorization, [EUA]) (US FDA, 2020; US FDA, 2020b) towards potentially co-creating safe decontamination and bioeconomy opportunities for recycling enormous volumes of PPE waste to protect our environment (Rubio-Romero et al., 2020; Alt et al., 2022).

A hallmark of the COVID-19 onset, in early months of 2020, was a tremendous lack of knowledge and understanding surrounding SARS-CoV-2, where the emphasis was placed on constraining and managing the spread of infection as there was no available vaccine to safeguard HCWs and citizens alike (Rowan and Laffey, 2020a; Rowan and Laffey, 2020b). Moreover, there was a marked gap in published information that addressed key needs to inform interventions and policies including viral pathogenesis, persistence, transmissiveness and efficacy of available disease prevention, control and waste management methods (Wu et al., 2020). There was a vast chasm in knowledge where the world scrambled to obtain and openly share new information in real-time, which would unlock appropriate solutions (Table 1). For example, at the time of writing, the top 16 "most cited" papers that were published in leading journals on core gaps and potential COVID-19 solutions collectively constitute a staggering 29,393 citations (Google Scholar) (Table 1). Having conducted a systematic literature review using Scopus and PubMed databases, the appearance of the key word "PPE" in journal publications increased by 71.4 % and 73.9 % respectively during the COVID-19 pandemic (Table 2). Over 7000 journal papers were published using key words "COVID-19" and "PPE". The trend showed substantial research and enterprise activities in the areas of "decontamination", "reuse" and "sterilization" generating 526 notable publications since the start of the COVID-19 pandemic (2020 to 2022 reporting period), where similar related studies had not been reported previously (Table 2). Of 516 papers of interest from the combined databases, 89 were included in this review to highlight key developments and emerging trends. The final set of complete information for this paper, represented in both Tables 1 and 2, was assembled and cross-referenced on the same day (19 October 2022). The purpose of this review is not to exhaustively digest and present copious data on the efficacy or shortcomings influencing appropriate intervention strategies (as there are many narrative and systematic reviews published on this topic cited here); but, it is to reflectively consider and articulate key findings that underpinned cues to action informing policies along with discussing commensurate opportunities that will potentially shape future needs for society, economy and our environment.

2. Observations from the early phase of COVID-19 pandemic

The World Health Organization (WHO) recommended that countries worldwide draw up a "Pandemic Plan" that would achieve clear results in managing pandemics from the early stages (Fusco et al., 2020). Each emergency in healthcare is characterized by different phases: mitigation, preparation, response and recovery (Public Health Emergency, 2012). National overarching plans provided scenarios that benefit from communication and cooperation between different multi-actors and sectors, such as healthcare management, HCWs, logistics, communication, finance and so forth (Public Health Management, 2012). In the absence of a vaccine, emphasis was placed on containing and managing the spread of SARS-CoV-2 outbreaks in the mitigation phase through the deliberate deployment of non-pharmaceutical interventions (NPIs) that addressed various modes of transmission, including contaminated contact surface and infectious aerosols (Charkaborty and Maity, 2020; Rowan and Moral, 2021). NPIs included exercising social distancing, where the WHO recommended wearing single-use N95s or FFP2 standard (or equivalent) facepiece respirators (FFRs) (WHO, 2020). A simplified holistic diagram highlighting the role of NPIs (including PPE) in breaking the chain of SARS-CoV-2 infection is illustrated in Fig. 1. Preventative and disease-controlling factors are typically focused on disrupting linkages between the infectious agent, susceptible host, mode of transmission, reservoir, mode of entry and mode of exit. Face shields and N95s or FFP2s and medical-grade face masks were also used by the general public; however, these were typically replaced by the use of improvised fabric face masks for public transport and in community settings as the months progressed and when COVID-19 vaccines were introduced (de Man et al., 2020). To protect frontline HCWs and to limit transmission, the WHO and US officials recommended wearing 100 to 300 million FFRS per month with the US having only 1 % of this in its supply chain (Lovelace, 2020).

When in sufficient supply, FFRs provide safe work environments for HCWs (Rowan and Moral, 2021). However, most countries experienced critical shortages of FFRs; therefore, it was essential to expedite alternative approaches to meet supply chain deficiencies where the US Food and Drug Administration (FDA) provided guidance for obtaining EUA to market

Table 1
Examples of "most cited" influential publications addressing critical new challenges and solutions for meeting PPE supply chain, disease mitigation and waste management during early stages of COVID-19 pandemic in 2020.

Citations	Topic	Paper title	Author(s)
10,553	Viral persistence	Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1	Van Doremalen et al. (2020)
5691	COVID-19 review	World Health Organization declares global emergency: A review of the 2019 novel coronavirus (COVID-19)	Sohrabi et al. (2020).
4477	Biocide efficacy	Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents	Kampf et al. (2020)
2284	Genome sequencing	Genome Composition and Divergence of the Novel Coronavirus (2019-nCoV) Originating in China	Wu et al. (2020)
1542	Environment, Prevention	COVID-19 outbreak: Migration, effects on society, global environment and prevention	Charkaborty and Maity (2020)
1276	Wastewater surveillance	First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia: A proof of concept for the wastewater surveillance of COVID-19 in the community	Ahmed et al. (2020)
946	Air pollution & COVID-19	Association between short-term exposure to air pollution + COVID-19 infection: Evidence from China	Zhu et al. (2020)
924	Lockdown, air quality	Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India	Mahato et al., 2020
384	Disinfection + Supply Chain + solutions	Challenges and solutions for addressing critical shortage of supply chain for personal and protective equipment (PPE) arising from COVID19 pandemic – Case study from the Republic of Ireland	Rowan and Laffey (2020a)
375	Hospital waste & wastewater	Disinfection technology of hospital wastes and wastewater: Suggestions for disinfection strategy during COVID-19 pandemic in China	Wang et al. (2020)
221	Disinfecting, Sterilizing face masks	Disposable masks: Disinfection and sterilization for reuse, and non-certified manufacturing, in the face of shortages during the COVID-19 pandemic	Rubio-Romero et al. (2020).
206	PPE reuse extended use	PPE and intensive care unit healthcare worker safety in the COVID-19 era (PPE-SAFE): an international survey. Journal of Critical Care.	Tabah et al. (2020)
175	COVID-19 Interventions	An environmental and health perspective for COVID-19outbreak: Meteorology and air quality influence, sewage epidemiology indicator, hospitals disinfection, drug therapies and recommendations.	Barcelo (2022)
148	PPP waste management	Environmentally Sustainable Management of Used Personal Protective Equipment	Singh et al. (2020)
107	Face coverings, reuse, waste management	Unlocking the surge in demand for personal and protective equipment (PPE) and improvised face coverings arising from COVID-19 – Implications for efficacy, re-use and sustainable waste management	Rowan and Laffey (2020b)
84	Sterilizing face masks	Sterilization of disposable face masks via standardized dry/steam sterilization processes; an alternative in fight against mask shortages	de Man et al. (2020).

devices (equipment) for the decontamination of N95s during this period of critical use (US Food and Drug Administration, 2020). For example, Tabah et al. (2020) received 2711 responses from a worldwide survey of 1797 (67 %) physicians, 744 (27 %) nurses, and 170 (6 %) allied HCWs on the availability and use of PPE caring for COVID-19 patients in intensive care units (ICU) where at least one piece of standard PPE was unavailable for 1402 (52 %), and 817 (30 %) reported reusing single use PPE, PPE was worn for a median of 4 h. Adverse effects of PPE were associated with longer shift durations and included heat (1265, 51 %), thirst (1174, 47 %), pressure areas (1088, 44 %), headaches (686, 28 %), inability to use the bathroom (661, 27 %), and extreme exhaustion (4992, 20 %). Battista et al. (2021) also reported adverse reactions in HCWs to PPE wearing during COVID-19. Alt et al. (2022) noted that sessional use, re-use, or use of alternative PPE to that of FFRs are the limited options that face HCWs during these periods of critical shortages. The US Centres for Disease Control and Prevention also published recommendations for extended use or limited re-use, (including decontamination), as potential mitigation approaches to offset known shortages of N95s. Mtetwa et al. (2021) reported on the effective decontamination of gowns during COVID-19.

Most countries experienced several "lockdowns" in order to contain and manage COVID-19 infection where the virus evolved into different variants of concern (VoC) through the process of viral mutational change enabled by incubation in large populations of infected people including asymptomatic carriers, over the pandemic period (Rowan et al., 2021). In the early waves of COVID-19, SARS-CoV-2 was reported to exhibit a higher transmission rate (Jiang and Shi, 2020), but a lower mortality rate (2–3 %) (Shi et al., 2020) to that of outbreaks caused previously by other coronavirus (such as 40 % for Middle East respiratory syndrome) (Shi et al., 2020). Due to its enveloped morphology, the SARS-CoV-2 virus has been shown to exhibit relatively low resistance to front-line disinfection, which became its "Achilles heel". Initial emphasis was placed on trying to protect the supply chain of PPE, particularly for HCWs, where there was a focus on keeping the R_0

Table 2
Systematic Review of Scopus and PubMed databases for journal publications containing key words on personal protective equipment (PPE) use, reuse and decontamination under EUA conditions during COVID-19 pandemic over period 2010 to 2022.

Scopus			PubMed		
Key word(s) used	Encompassing COVID-19 pandemic [2010 to 2022]	Prior to COVID-19 pandemic [2010 to 2019]	Key word(s) used	Encompassing COVID-19 pandemic [2010 to 2022]	Prior to COVID-19 pandemic [2010 to 2019]
PPE	20,831	5943	PPE	46,554	12,164
PPE + COVID-19	7594	0	PPE + COVID-19	7081	0
PPE + COVID-19 + Sterilization	211	0	PPE + COVID-19 + Sterilization	388	0
PPE+ COVID-19 + Decontamination	102	0	PPE + COVID-19 + Decontamination	290	0
PPE + SARS-COV-2	1500	0	PPE + SARS-COV-2	6125	0
PPE + Disinfection + SARS-CoV-2	128	0	PPE + Disinfection + SARS-CoV-2	498	0
Decontamination + N95	232	3	Decontamination + N95	243	17
PPE + Reuse	150	5	PPE + Reuse	169	8

Fig. 1. Role of key interventions strategies in breaking the chain of COVID-19 infection.

value below 1 in order to limit the number of SARS-COV-2 infected cases requiring hospital care (particularly for vulnerable patients that may need ventilator assistance in intensive care unit ICU) (Rowan and Moral, 2021).

A hallmark of the initial months of COVID-19 was the introduction of creative means of ensuring the continuity of a vital PPE supply chain including 3-D printing of face shields, bespoke production of Starmed Hoods for point-of-use in ICU (Rowan and Laffey, 2020b), use of blockchain to manage and distribute PPE to essential HCWs (Fusco et al., 2020; Nandi et al., 2021), and reuse and decontamination of single use PPE where severe shortages occurred due to this pandemic situation (Rowan and Moral, 2021). For example, blockchain has been increasingly applied to inform risk in healthcare management, as a strategic tool to strengthen efficient and effective evidence-based decision making. Fusco et al. (2020) reported on the benefits of using blockchain combined with artificial intelligence systems to affect a trace route for COVID-19 safe clinical practice. Smart use of blockchain allows for the creation of a generalizable predictive system that could contribute to the containment and management of pandemic risk nationally (Fusco et al., 2020). At the outset of COVID-19, Rowan and Laffey (2020b) reported on the trial use of bleach (sodium hypochlorite at ≤4000 ppm), along with a counter water immersion phase to remove residuals, for testing the disinfection performance of Starmed Hoods for ICU. This point-of-use chemical disinfection strategy was not put into practice due to operator concerns over the lingering unpleasant chlorine odor; also, Viscusi et al. (2009) measured the filtration performance of two FFR models submerged into a range of sodium hypochlorite solutions (0.525 %–5.25 % sodium hypochlorite) and noted some degradation in filtration performance, but not below acceptable levels.

In Ireland, as well as many countries internationally, responses and communication to the general public was coordinated by the government through the Department of Health where there was reliance on contributions from subject matter experts across various fields ranging from medical device manufacturing to clinicians/epidemiologists that were connected via a dedicated mobile WhatsApp group. This holistic approach helped to inform a rapid and flexible response to shaping new effective policies, including appropriate disease mitigation strategies. This unified approach was a stand-out abiding "response" feature from this shared COVID-19 pandemic experience as it hurdled conventional silo-based scenarios through holistic engagement where key individuals were joined by a common purpose to solve a societal challenge. This essentially unlocked the collective intellectual and creative wealth of multi-actor stakeholders to inform the government including generating and openly sharing vital information surrounding COVID-19 which informed effective guidelines and policies to constrain and manage the spread of the SARS-CoV-2 virus. Most countries had a limited number of critical-use ventilators and emphasis was also placed on the bespoke production of key equipment and safe reuse. Logistically, this was challenging given that all countries were also similarly affected by the same supply chain shortage issues for PPE; this was supported through the fast-tracking research funding nationally, and internationally from a bottom-up perspective. Addressing the safe reprocessing of vital single-use PPE for reuse applications was a complex and underappreciated task. PPE is manufactured, tested, verified and validated under very strict conditions that include an appropriate terminal sterilization step, which informs authorization by regulators, such as the FDA. As PPE items consist of varying materials where many are heat sensitive, there is a commensurate need to match this need with the use of appropriate and effective decontamination and sterilization modalities. For example, the choice of a decontamination method for the reuse of PPE must also negate any dysfunctionality post-treatment, such as retaining filtration efficacy (for FFRs), comfort fit, material compatibility and safety. Original equipment manufacturers (OEMs) of medical devices (including PPE) had not envisaged, possibly ever, that there would be a requirement to reuse PPE where vital supply was disrupted due to the pandemic. OEMs willingness to share knowledge and to provide expert advice contributed to unlocking this challenge where EUA was granted by regulators for PPE reuse using limited treatment technologies (example, VH2O2 used alone or with Ozone). At the outset of the COVID-19 pandemic, there was a gap in evidence-based publications on the persistence and survival of Coronavirus on contact surfaces (example, Kampf et al., 2020 that has reached 4477 citations) (Table 1). Based on tacit and subject matter expert knowledge of working closely with disinfection and sterilization modalities over many decades, a paper was framed on candidate appropriate technologies that could potentially address safe decontamination of PPE under EUA conditions (Rowan and Laffey, 2020a [386 citations]). The timing of this published paper also coincided with EUA US FDA on alternative strategies for PPE reuse (Rowan and Laffey, 2020b; Alt et al., 2022). Interestingly, the duration to write, review, accept and appear online in the journal in open access format was five days, which reflected the urgency in responding to critical COVID-19 knowledge gaps. At the then time of writing (3 April 2020) this paper, the global number of confirmed COVID-19 cases had reached 1,000,249 with 51,515 deaths which markedly contrasts with current epidemiology data recording 625,359,756 cases and 6,569,533 deaths (19 October 2022). Candidate technologies proposed in April 2020 for safe PPE decontamination, such as the use of vaporized hydrogen peroxide (VH2O2), mild heating and UV irradiation, remain the most popular methods used today. The potential use of VH2O2 for PPE decontamination was informed by the timely systematic review paper of McEvoy and Rowan (2019), which comprised a SWOT analysis on the use of VH2O2 compared with other technologies for terminal sterilization applications, such as physical (gamma-, x-ray, electron-beam) and gaseous (ethylene oxide) methods. This McEvoy and Rowan (2019) paper was written to provide valuable information in order to advance the field of terminal sterilization for established medical device manufacture and safe use, and not for PPE reuse.

It was also appreciated that Coronavirus was a large enveloped virus; therefore, it was likely to be susceptible to the lethal action of frontline disinfectants. Thus, moderate to high-level disinfection processes (6 $\log_{10}$ reduction in mycobacterial cells, but not bacterial endospores) could be theoretically applied for the safe reprocessing of PPE during COVID-19 without the need for full 12 D reduction in bacterial spores that is allowed for in a sterilization processes. A D value is the time taken to reduce a population of microorganisms by 1 $\log_{10}$ order using a concentration of disinfectant or steriliant (Rowan, 2019). During the early phase of COVID-19, the US FDA and US officials authorized similar decontamination modalities to address pressing PPE supply chain deficiencies under EUA for the reprocessing of PPE (encompassing Umbrella EUA for surgical masks, N95 and other respirator EUA and face shields and other barrier EUAs) during this pandemic that was restricted to a limited number of modalities, such as the use of VH2O2 (US FDA, 2022). At no time was it deemed appropriate to use physical radiation modalities (x-ray, gamma and electron-beam) or ethylene oxide gas for the reprocessing of contaminated PPE during COVID-19. Recent publications in this area corroborated this approach where Haedi et al. (2021) reported the decreased functionality of FFRs after gamma irradiation treatments. US FDA (2020) advised that "once availability of PPE (including facemasks) returns to normal (non-EUA conditions), healthcare facilities should promptly resume conventional practices".

There was a commensurate surge in interest in the use of different types of decontamination methods focused on addressing infectious aerosols and contaminated surfaces including PPE applications with some success. Viana Martins et al. (2022) reviewed 1229 studies from two databases of which only 16 studies reported on methods to "recondition PPE". However, there was frequent variance in the type and level of challenge microorganism(s) used where some researchers used SARS-VoC-2 for PPE decontamination. However, the majority of these in vitro studies did not encompass PPE functionality and material compatibility testing as part of the reported decontamination methods. Various other sophisticated decontamination methods were applied for PPE decontamination with reported successes, including the use of VH2O2 plasma vapor, ionized VHO2 (Cramer et al., 2021), plasma-generated ozone and reactive oxygen species (ROS) (Huang et al., 2022), supercritical CO_2 (Bennet et al., 2021), photoactivated methylene blue (Floreine et al., 2022). For example, plasma-ROS treated PPE (N95s) maintained acceptable mechanical and functionality properties for point-of-use decontamination applications (Huang et al., 2022). Lendvay et al. (2022) reported on the successful decontamination of N95s artificially inoculated with 2 SARS-CoV-2 viruses using novel methylene blue photochemical treatments where FFR integrity was maintained after five processing cycles. The same authors noted that one FFR model failed after five cycles using FDA-authorized VH2O2 plus ozone decontamination method that was included as a comparative control. McAvoy et al. (2021) reported on the successful use of 3D-printed frames to enable reuse, extended-use and improved fit of N95 and KN95 respirators. However, Chen et al. (2019) reported that 3D-printed polymers are less stable than injection molding fabrication when exposure to terminal sterilization by VH2O2 and electron beam technologies.

There was a concerted focus on testing less complicated, more available and affordable disinfection approaches for PPE reuse. For example, Côrtes et al. (2021) evaluated the re-use of 45 surgical masks and 69 respirators by analyzing their performance and safety before and after decontamination using oven, thermal drying, autoclave, and hydrogen peroxide plasma vapor. In addition, 14 used respirators were analyzed after work shifts before and after decontamination using reverse transcription polymerase chain reaction (RT-qPCR) and viral culturing. Oven decontamination (75 °C for 45 min) exhibited the simplest decontamination method that maintained acceptable physical and filtrations performance of treated masks and respirators for at least five processing cycles. Reprocessed respirators used in work shifts (hospital settings) were evaluated positively by users in terms of functionality and comfort, even after three decontamination cycles. Alt et al. (2022) noted that "appropriate decontamination technologies for PPE reuse under EUA FDA conditions must meet the following criteria: (1) include screening and replacement processes for these FFRs not suitable for reuse; (2) effectively inactivate SARS-CoV-2 or representative virus and other relevant bioburden on the FFR; (3) be compatible with the FFRs to avoid rendering it dysfunctional; (4) be available and practical for healthcare settings; and (5) minimize risk to operators of the decontamination equipment and end-users alike".

Clustering of decontamination and sterilization activities and services for PPE reuse under EUA pandemic conditions was centered around the use of regional hospitals, such as in Ireland that was coordinated by the Health Service Executive (HSE) in partnership with Science Foundation Ireland (SFI), academic institutions, industry and with established terminal sterilization companies. A limited number of published studies had used actual Coronavirus strains as a bioindicator for establishing decontamination efficacy and sterility assurance levels of treated PPE during the COVID-19 pandemic. It is appreciated that the reprocessing and sterilization industries are a bastion of rigor that communicates closely with regulators to ensure compliance with standards in order to safely decontaminate and sterilize products. Thus, several non-thermal candidate laboratories pilot or commercially-available technologies used for food processing (such as gas plasma, high pressure, pulsed electric fields, photonics and so forth (Gómez-López et al., 2021)) that would not be deemed appropriate for PPE reprocessing for point-of-use healthcare applications until due to the nature of their biocidal action, material compatibility and lack of data to support regulator approval. Despite the establishment of PPE reuse methods in healthcare facilities in Ireland, there was a lack of interest in their use by HCWs. Emphasis was always placed on ensuring a continuous supply chain of new PPE items during the COVID-19 pandemic. Absent was the establishment of independent testing laboratories nationally for verification and validation of reprocessed PPE for in-house healthcare applications during COVID-19. However, a new European pandemic response hub, managed by the University of Galway, Ireland, now coordinates and supports research and enterprise in this area including provision for mitigating against future pandemics.

3. Developments during the COVID-19 pandemic

Through the passage of time, new combinational approaches were adopted to inform disease prevention and control including the introduction of effective COVID-19 vaccines (Table 3). Examples of interesting activities and innovations include the modeling of COVID-19 infection data and positive case occurrences (Zeroual et al., 2020; IHME COVID-19 Forecasting team, 2021; Rowan and Moral, 2021), and the use of machine learning and blockchain to review data from a supply chain perspective. For example, Haug et al. (2020) combined statistical modeling and machine learning techniques and estimated that wearing a mask yields a reduction of R_0 between 1.8 % and 12 %, while social distancing contributed to a reduction of approximately 20 %. Genomic, next-generation sequencing and bioinformatic breakthroughs also provided key information on countermeasures. Longitudinal modeling studies yielded new information on the efficacy of COVID-19 mitigation strategies and surveillance of transmission rates in various susceptible populations internationally, where evaluating related data over short timeframes provides limited value (Rowan and Moral, 2021). Efficacy of front-line biocides must also consider the appropriateness for meeting the emerging SARS-CoV-2 variants of concern that differed in transmissiveness and pathogenesis. There was a holistic sharing of key findings by multi-stakeholders for solutions that included the use of the Quintuple Helix Hub approach (combination of academia-industry-healthcare-government-society) to support research, development and innovation linked to education. Interestingly, there was a commensurate push for the digital transformation of adjacent industries including additive manufacturing and food systems (Rowan et al., 2022), which can potentially improve efficiencies in terms of monitoring, surveillance, sustainability, and automation. Currently, there are 706 established or new European Digital Innovation Hubs (EDIHs) where there are opportunities to align some of these appropriate EDIHs for meeting pandemic disease response, innovation, education and training (Table 3) (Rowan et al., 2022). These could also support new SMEs, start-ups, and entrepreneurs, particularly with a focus on transitioning to sustainable solutions, which may also inform new businesses and possibly, future technology disruption (Rowan and Casey, 2021). Opportunities to advance pandemic disease preparedness and responses could also be further supported through bespoke specialist training using immersive and educational technologies.

4. Impact of SARS-CoV-2 'variants of concern' of PPE usage – bracing for a winter COVID-19 surge

PPE encompassing face masks (medical grade, FFP2, N95s) remain an important intervention strategy to constrain and manage SARS-CoV-2. Despite the availability of effective vaccines and antiviral drugs such as

Table 3
Examples of new issues, activities and solutions arising for meeting PPE supply chain shortage, disease mitigation and waste management during COVID-19 pandemic.

Citations	Topic	Paper title	Author(s)
752	Symptoms (smell, taste)	Anosmia and Ageusia: Common Findings in COVID-19 Patients	Vaira et al. (2020)
326	Infection modeling	Modeling COVID-19 scenarios for the United States	IHME COVID-19 Forecasting Team
301	Diagnostics	COVID-19 diagnostics and context	Wesssleder et al. (2020)
226	Wastewater surveillance	Wastewater surveillance for population-wide Covid-19: The present and future	Daughton (2020)
212	Blockchain in supply chain bioeconomy	Redesigning Supply Chains using Blockchain-Enabled Circular Economy and COVID-19 Experiences	Nandi et al. (2021)
181	Energy & Environ footprint	The energy and environmental footprints of COVID-19 fighting measures – PPE, disinfection, supply chains	Klemeš et al. (2020)
177	Quadruple interactive HUBs	Unlocking challenges and opportunities presented by COVID-19 pandemic for cross-cutting disruption in agri-food and green deal innovations: Quo Vadis?	Rowan and Galanakis (2020)
171	Multi- actor approach	COVID-19: A Call for Physical Scientists and Engineers	Huang et al. (2020)
116	Environmental pollution	Occurrence of personal protective equipment (PPE) associated with the COVID-19 pandemic along the coast of Lima, Peru	De la Torre et al. (2021)
112	Open research datasets	COVID-19 Data Hub	Guidotti and Adria (2020)
87	3 D printed PPE	3-D Printed Protective Equipment during COVID-19 Pandemic.	Wesemann et al. (2020)
79	Blockchain in Healthcare	Blockchain in Healthcare: Insights on COVID-19	Fusco et al. (2020)
70	Sustainable PPE	COVID-19 Creating another problem? Sustainable solution for PPE disposal through LCA approach	Kumar et al., 2021
62	PPE pyrolysis waste to energy	Current plastics pollution threats due to COVID-19 and its possible mitigation techniques: a waste-to-energy conversion via Pyrolysis.	Aragaw and Mekonnen (2021)
53	Modeling of Non- pharmaceutical interventions (NPIs)	Disposable face masks and reusable face coverings as non-pharmaceutical interventions (NPIs) to prevent transmission of SARS-CoV-2 variants: Role of new sustainable NPI design innovations and predictive mathematical modeling	Rowan and Moral (2021)
33	Alternative sanitizing for Masks	Photocatalytic Rejuvenation Enabled Self-Sanitizing, Reusable, and Biodegradable Masks against COVID-19	Li et al. (2021)
30	Biodegradable Multifunctional Surgical Face masks	Biodegradable and multifunctional surgical face masks: A brief review on demands during COVID-19 pandemic, recent developments, and future perspectives	Badaahmadi et al. (2021)
21	Sustainable PPE – materials and recycling	Key ingredients and recycling strategy of personal protective equipment (PPE): Towards sustainable solution for the COVID-19 like pandemics.	Singh Siwal et al. (2021)
15	Machine learning – case mortality	Identifying mortality factors from Machine Learning using Shapley values – a case of COVID19	Smith and Alvarez, 2021

Paxlovid, COVID-19 cases caused by a mix of new VoC remain a worry given that these collectively represent one in three new SARS-CoV-2 infections in the US (Wang et al., 2022). COVID-19 cases are rising in Europe and the UK, where these VoC have taken hold (Goodman, 2022). The Omicron subvariant BA.5 causes most COVID-19 infections in the US (Smith-Schoenwalder, 2022), accounting for 88 % of new infections. Those with weakened immunity will be particularly vulnerable (Rhee et al., 2022), where recent research intimates that the last laboratory-created antibodies do not provide adequate protection against these VoC (Cao et al., 2022). These VoC descend from slightly different branches of the Omicron lineage, and this "convergent evolution" infers that several VoC can be co-circulating in our population at the same time as we enter winter. With a reduced emphasis on wearing face masks in many countries, there will be a co-challenge to meet potential surges in both COVID-19, influenza and possibly Norovirus (winter vomiting) that will place added pressure on our healthcare system and our HCWs. Interestingly, adherence to NPIs practices generally reduced the incidence of influenza and Norovirus cases over the past two winters. Real-time assessment of the large mix in VoC is becoming challenging as countries reduce surveillance (WHO, 2022). However, <10 % of the US population (14.8 million people) have received an updated COVID-19 bivalent booster vaccine, which is of concern. Thus, the use of PPE, particularly for frontline HCWs remains important; and therefore, the commensurate need to address effective sustainable clinical waste management.

Published work intimates that VoC would be similarly sensitive to disinfection and PPE as preventive measures (Rowan et al., 2021). Meister et al. (2021) reported disinfection effectiveness against SARS-CoV-2 VoC B.1.1.7 and B.1.351 using heat, soap and ethanol where treatment was carried out using a variety of artificially-seeded surfaces including face masks. While society now has effective disease mitigation strategies, we cannot become complacent which includes continued investments in vaccines and antibody therapies. Of concern is societal fatigue towards the use of NPIs (Michie et al., 2020), particularly when one considers that we will be living with COVID-19 for many years ahead. Rhee et al. (2022) surveyed COVID-19 infection control policies at 30 leading US academic hospitals in the context of the initial pandemic surge of the SARS-CoV-2 omicron variant and found that infection control practices vary substantially. The authors recommended clearer public health guidance and transparency around hospital policies that also aligns with meeting VoC responses, in order to facilitate consistent and harmonized standards.

5. Surge of PPE use and impact on waste management and our environment

The US healthcare facilities generate an estimated 1 million tons of non-infectious plastic waste every year where there are opportunities to improve recycling (Healthcare Plastics Recycling Council, 2019). Creative means of monitoring and surveillance of COVID-19 pandemic have been applied including reporting the occurrence of this virus in municipal waste that would reflect community-level transmission rates (Daughton, 2020; Barceló, 2020; Ahmed et al., 2020) (Table 1). There is also a pressing need to address appropriate clinical waste management for used PPE (Rubio-Romero et al., 2020; Rowan and Laffey, 2020b). Given the sure in single-use PPE that contains plastic globally (De la Torre et al., 2021) there is commensurate interest in effective and alternative approaches to clinical waste management. For example, Zhao et al. (2022) describe a novel pyrolysis process for used PPE that enables energy recovery through a detailed life cycle assessment approach and includes sustainability. The authors point to the environmental advantages of reducing 35.42 % of total greenhouse gas emissions from the conventional incineration and 43.50 % of total fossil fuel use from landfill processing, the optimal number, sizes, and locations of established facilities within PPE processing system in New York State where one integrated fast pyrolysis facility is used in Rockland County.

There is increasing evidence of PPE accumulation in our environment including the marine that has accelerated interest in identifying workable solutions. Waste PPE was have been reported globally that contaminates our natural capital and habitats (De la Torre et al., 2021). Consequently, there is a surge in interest in the development of alternative biodegradable materials to replace plastics in PPE including considering waste-to-energy conversion (Badaahmadi et al., 2021). It is estimated that some 44 million non-woven PPE items are used by frontline HCWs every day, resulting in some 15,000 tons of waste that are destined for landfills or incineration. Alt et al. (2022) noted that while many materials in PPE are recyclable, SARS-CoV-2 contamination significantly influences such disposal strategies, and this coupled with the natural resource consumption during manufacture may impact our natural environment. Alt et al. (2022) also evaluated and validated technologies suitable for the decontamination and re-use of contaminated N95 FFRs in response to the COVID-19 pandemic. Multiple low-temperature steam (65 to 71 °C) and vaporized hydrogen peroxide technologies were shown to be successful that inactivated feline calcivirus (FCV, $>3 \log_{10}$) and *Mycobacterium* species ($\geq 6 \log_{10}$) (employed as representatives on the contamination challenge) without affecting the performance of the treated PPE. This work was reported to be suitable for 10 to 20 decontamination cycles of the same PPE. This is potentially a "game-changer" as the deployment of commercial VH2O2 processes could decontaminate large amounts of PPE making it safe for circular bioeconomy applications and long-term sustainability, including reducing PPE waste destined for landfill or incineration (Aragaw and Mekonnen, 2021). Several studies have corroborated the effective use of VH2O2 technologies to decontaminate N95 face masks (Jatta et al., 2021; Deer et al., 2022). Alt et al. (2022) also reported that there are additional challenges to be considered for the reuse of PPE that includes user acceptance, traceability and stock management. Doos et al. (2022) and Kea et al. (2021) reported that the reuse of non-decontaminated PPE worn by HCWs is not an appropriate practice.

Industrial VH2O2 is a strong candidate technology for sustainable PPE waste management as it meets scalability, penetration, and compatibility with materials including innovations in sterilization chamber design and process development (McEvoy and Rowan, 2019). Not all sterilization technologies would be deemed appropriate for large-scale decontamination of PPE waste. For example, the challenges of using ethylene oxide (EO) relate to the hazardous and carcinogenic nature of the gas combined with prolonged treatment times (McEvoy and Rowan, 2019; McEvoy et al., 2021). While radiation is a relatively rapid process leaving no unwanted toxic residues, it is limited by the availability of the radiation source (cobalt), in the case of gamma and not applicable (McEvoy and Rowan, 2019). Emerging non-thermal technologies, such as cold gas plasma (Hayes et al., 2013; Qin et al., 2022), have the potential for novel point-of-use decontamination of clinical waste before transport to landfill or incineration; thus, offering new opportunities for reducing, reusing and recycling. Qin et al. (2022) reported that cold gas plasma (CAP) destroyed six major epidemic strains of SARS-CoV-2 variants of concern within 300 s, where this CAP method affects the SARS-CoV-2 spike protein rather than damaging viral RNA through an oxidative reaction. The presence of soiling on surfaces must always be considered from a cleaning perspective as the presence of organic matter can affect disinfection efficacy on contaminated surfaces including medical devices (Rowan et al., 2021).

6. Addressing future circularity and sustainability of single-use PPE

There has been a marked surge in research interest focusing on the future sustainability of medical devices, particularly, the role of using reprocessing versus single-use plastic items. The sustainability of medical devices (particularly, single-use PPE) has intensified by meeting supply chain shortage issues arising from the COVID-19 pandemic that has placed increased emphasis on reuse (where appropriate), and clinical waste management. Popular circularity and sustainability topics and activities have been captured in Table 4. In addition, use of life cycle assessment (LCA) tools to address all end-to-end stages for medical devices from design thinking to authorized commercial use will help inform resource consumption, carbon footprint, supply chain and transport energy efficiency,

Table 4
Examples of new and related research and innovation informing the future circularity and sustainability of medical devices (including PPE) arising a consequence of COVID-19 occurrence.

Topic(s)	Description of research and innovation activities	Reference
Environmental Impact Assessment LCA assessment Circularity assessment	➢ 16 different environmental impact categories highlighting superior use of reprocessed devices over single use in 13 categories with focus on electrophysiology catheter. Also informed by LCA. ➢ Healthcare could cut emissions by half for some devices if opting for regulated, reprocessed "single-use" items	Schulte et al. (2021)
Resource Consumption & Emissions; New job creation	➢ Avoiding use of virgin materials, remanufacturing alternators can environmental impacts of resource consumption, emissions [reducing abiotic resource use and the Global Warming impact (GWI)] – Uses LCA.	Peters (2016) Zhang et al. (2020) D'Adamo and Rosa (2016)
Use of VH2O2 for PPE waste management	➢ Development and validation of technologies for decontamination and reuse of contaminated N95 filtering facepiece respirators with provision for future sustainable waste management	Alt et al. (2022).
Rapid manufacturing; 3D printing; Biocompatability Recycling challenges	➢ Consider material composition, toxicological end-points and improvements in compatibility testing given future sustainability and reuse opportunities for medtech ➢ Recycling of complex medical device products needs extensive material flow analysis to make it economically and ecologically reasonable ➢ The more complex a device, the more process steps, energy, and resources are needed for recycling ➢ Complex devices may have specific requirements for collection and disposal after use from an infection-prevention perspective and may contain complex materials not suited to municipal waste management & recycling infrastructure (including Green technology)	Antonini et al. (2021) Hayes et al. (2013) Gopinath et al., 2020 D'Adamo and Rosa (2016) Eze et al. (2020) Lee et al. (2017)
CE concept using R-strategies	➢ *Design smarter* [Refuse, Rethink, Reduce] ➢ *Extend lifetime* [Reuse, Repair, Refurbish, Remanufacture, Repurpose] ➢ *Circularly end-point activities*: Recycle and Recover	Potting et al. (2017)
Reuse of Polyvinyl Chloride (PVC)	➢ Recycle PVC several times (most widely used plastic in medical devices) without loss of critical properties	I'Ons (2021)
Design thinking	➢ Design medical devices smarter for circularity that includes appropriateness for reprocessing and sterilization ➢ Design from day one with disassembly and cleaning in mind, including reducing number of device components	I'Ons (2021)
Improve energy efficiency	➢ Improving energy efficiency and opting for clean energy source could reduce overall costs ➢ Additive manufacturing can reduce material waste by as much as 90 % compared to conventional manufacturing and can speed up device prototyping and testing	I'Ons (2021)
Logistical and design challenge	➢ Consider device materials in sustainable design ➢ For example, disposable surgical drapes contain polypropylene and polyethylene, each can be recycled, but used together they cannot be recycled.	La Plante (2022)
Reduce carbon footprint	➢ Recycled materials can be used without loss of technical properties or need for addition of virgin materials ➢ For example, recycled polyethylene terephthalate (PET) has 79 % lower GHG emissions that virgin PET.	La Plante (2022)
Multi-actor collaborations	➢ Work with Medical Device component and OEM manufacturers to advance circular medical device production, and to move away from traditional "take-make-waste" linear systems.	La Plante (2022) Rowan and Laffey (2020b)
AI, automation and use of novel diagnostic technologies	➢ Consider automating processes including use of artificial processes to potentially reduce resources and disinfection along with future sustainability production and waste management ➢ Role of novel diagnostic techniques in monitoring reprocessing and sterilization of devices	McEvoy et al. (2021)
Role of Supply Chain and Transport	➢ What steps are used to reduce energy, water and chemical use ➢ Reduce transport of waste from used medical devices by recycling in same region to reduce carbon footprint	La Plante (2022)
Research translation, Education, Advocacy	➢ Surveyed 'state-of-the-art' environmental sustainability research in anaesthesia and critical care where avoid, reduce, reuse, recycle and reprocess addressed ➢ Moving beyond clinical care, energy (renewables vs fossil fuel) and energy efficiency are important influencers in healthcare's ecological footprint.	McGain et al. (2020).

profitability, automation for future circularity and sustainability. Lessons can also be learnt from adjacent industries on the combined use of other sustainability tools that has influenced innovation in packaging (Ruiz-Salmón et al., 2020; Almeida et al., 2021;). There is enhanced interest among researchers in the incorporation of smart bioactive materials into medical devices that exhibit virocidal and bacteriocidal properties, which could potentially be used in the design and development of more sustainable innovations (Masterson et al., 2021); however, the appropriateness of these new materials to tolerate established high-level disinfection or sterilization processes would need to be incorporated into new product evaluation and validation including maintaining the functionality of new design innovations during testing or reuse.

Addressing such challenges is likely to have potential broader disease preventive benefits including addressing antimicrobial resistant bacterial and fungal pathogens (AMRs) that are at a crisis point globally (Garvey et al., 2022). Masterson et al. (2021) reported, for the first time, the development of a low-temperature extrusion process for the production of GRAS bioactive-polymer loaded compounds for targeting such AMR bacteria that may also be suitable for decontamination processes. There is significant scope to develop appropriate sustainability tools for evaluating the potential impact of applied decontamination technologies on the environment (Hayes et al., 2013) including elucidating cellular mechanisms of inactivation (Farrell et al., 2013). The use of life cycle assessment (LCA) confirmed that more sustainable strategies for the disposal of PPE waste are needed (Kumar et al., 2021). However, published studies have also highlighted that data generated by medical-device-focused researchers would benefit from having an understanding of decontamination and sterilization technologies in their method (Rowan and Moral, 2021). This knowledge gap can be addressed by delivering specialist training on medical device reprocessing and terminal sterilization to academia and other stakeholders including SMEs, start-ups and entrepreneurs; thus, co-creating solutions in the adjacent circular bioeconomy or digital technologies domains (Table 3). The latter can be enabled and accelerated through sustainable business models that will de-risk investments in innovations (Rowan and Galanakis, 2020).

7. Emerging opportunities and challenges for PPE supply chain

Table 5 describes 24 observations from tackling critical PPE supply chain challenges and other adjacent COVID-19 activities and will inform the ongoing and future pandemic response plans with opportunities for promoting innovation and sustainability that will potentially benefit society, the economy and the environment. There is an emergence of opportunities to consider such as automation using robotics in medicine and healthcare including transforming reprocessing of complex medical devices (such as endoscopes) in healthcare (Allescher et al., 2022). This includes keeping

Table 5
New observations and lessons learnt from tackling critical PPE supply chain challenges during COVID-19 pandemic.

No.	Topic	Reference
1.	Efficacy in forging **multi-actor contributions to techno-, socio-economic** and environmental challenges for **real time solutions** in innovation and policies underpinning pandemic plan led by Government with subject-matter experts	Rowan and Laffey (2020a)
2.	**Global terminal sterilization technologies** have potential to scale and treat large volumes of PPE waste during pandemic for future recyclable options	Alt et al., 2022
3.	Importance of open **real-time communication** (selecting appropriate channels, messaging, timing) and **Open-Access dissemination** for sharing and reflecting upon break-through solutions (ex. COVID-19 tracker phone apps)	Zhang et al, 2022
4.	Greater need for **education, training and awareness** of the role of PPE supply chain, infection microbiology, disinfection/sterilization modalities, sustainability and circular bioeconomy in universities with industry	Rowan and Moral, (2021)
5.	**Co-creation of regional clusters** and convergence of **multi-actor innovation hubs** nationally for pandemic response plans	University of Galway (2022)
6.	Interest in **sustainable management of PPE waste**	Singh et al. (2020)
7.	**Reliance on front-line HCWs** to deliver on critical disease prevention and control service that can be prolonged and **highly stressful** where there is limited understanding on **mental health** and wellbeing including long-term wearing of medical face masks and possible use of reprocessed PPE	Tabah et al. (2020) White et al. (2021) Kea et al. (2021)
8.	Repeat waves of COVID-19 infections introduces **societal fatigue** in terms of adherence to mandatory lockdowns and restricted social movement; imposing future lockdowns will challenge society further with present-day economic pressure caused by increased cost of living, energy/commodity crisis, inflation and potential emergence of a global economic recession.	Michie et al. (2020) Rowan and Moral (2021)
9.	Reliance on single-use-plastic based PPE in healthcare globally can have a dramatic and underestimated impact on **environmental pollution** during a pandemic with urgent need to identify alternative biodegradable polymers in PPE design and appropriate clinical waste management	Kumar et al. (2021) Rowan and Galanakis (2020)
10.	SARS-CoV-2 virus mutated and changed to variants of concern that is likely to persist for many years akin to influenza, where there is requirement for regular monitoring to confirm efficacy of vaccines and boosters. Also, despite genetic adaptive changes to virion genome, **VoC are similarly sensitive to front-line non-pharmaceutical interventions (masks)** and to non-specific **chemical disinfectants and physical treatments**. Serendipitously, society was fortunate that this is a complex enveloped virus rendering it less likely to persist for long time on surfaces and readily disinfected	Rowan et al. (2021) Rhee et al. (2022) Meister et al. (2021)
11.	Creativity and ingenuity of society in **improvising and problem solving** ranging from improvised wearing of fabric-based face mask to determining indicative levels of virus in communities by monitoring of municipal wastewater, to tracking, modeling and reporting on COVID-19 globally in real-time dashboard managed by Johns Hopkins University	Rowan and Laffey (2020b). Rowan and Moral (2021)
12.	Unlike deadly Spanish flue of 1918 where rate of international transmission was comparatively slow due to absence of commercial air travel; COVID-19 **rapidly spread globally**, but society had means of disease counters measures.	Sohrabi et al. (2020).
13.	OEMs of medical devices (PPE) and contract sterilization pivoted to supporting and providing solutions for what are typically single use devices	Alt et al., 2022
14.	**Regulators** and healthcare authorities **acted rapidly** to develop appropriate pandemic plan including EUA for PPE reuse such as point-of-use in healthcare	US FDA 2020 WHO, 2020
15.	Despite suite of physical and gaseous sterilization modalities, and greater appreciation of efficacy of emerging non-thermal technologies (such as use in food industry), reprocessing of PPE for point-of-use in healthcare under EUA is likely is restricted to use of a limited number of validated modalities until such time that other modalities are appropriately developed, tested, commercially scaled and meet regulatory need with matching ISO standards	Gómez-López et al. (2021) Floreine et al. (2022) Lendvay et al. (2022)
16.	**Fast tracking funding** in research and enterprise to develop solutions, which reduces red-tape and barriers to innovation and open knowledge sharing has been seen as impactful and beneficial. Such as 3 D printing of medical devices, and bespoke production of replacement Starmed hoods for ICU.	McAvoy et al. (2021) Told et al. (2022) Rowan and Laffey (2020b)
17.	Many developed small countries including Ireland could afford maintaining single use PPE supply chains through procurement, and benefited from early freely available vaccines – however, there is a greater need in society to **share and expedite knowledge, innovation and solutions** with **developing countries** that are equally addressing co-morbidities in terms of HIV and TB	United Nations (2021)
18.	Reliance on mainstay PCR in healthcare **as sustaining innovation**; but, developments in digital technologies (real time monitoring, models, immersive technologies, blockchain) along within in situ 3D printable sterilized devices show promise as **disruptive innovation** in pandemic plan	Rowan and Moral (2021) Huang et al. (2020)
19.	Due to adopting effective face mask wearing and use of other non-pharmaceutical interventions (NPIs), there was a **marked reduction or absence** in the occurrence of influenza and winter vomiting Norovirus that challenge healthcare during winter seasons – their reemergence (including RSV) will place **added pressure on embattled healthcare system** that are already **playing catchup** from a resource and HCW fatigue perspective. It is likely that combined COVID-19 + Flu + RSV will present significant challenges.	Speare-Cole (2021) Agha and Avner (2021)
20.	**Wearing of face masks** in society (out with typically healthcare) became the **social norm** and will be used in **healthcare for the foreseeable future**	Rowan and Moral (2021)
21.	Only in the passage of time, such as through **reflection on longitudinal mixed-methods studies** including modeling will true effectiveness of interventions be understood for **harmonizing global pandemic response plan**	Rowan and Moral, 2021
21.	**Strong community engagement** including bespoke 3 D printing of face shields in local schools	Wesemann et al. (2020)
22.	Emergence of opportunities **for digital technologies** and use of machine learning during COVID-19 pandemic	Allescher et al. (2022) Taylor (2022)
23.	Surveillence of COVID-19 by use of **sewage as epidemiological indicator**	Barceló (2020)
24.	VoCs adopt and co-circulate in society, but **use of disinfectants are effective**.	Meister et al. (2021) Rhee et al. (2022)

Abbreviations: Variants of Concern (VoC); Non-pharmaceutical Interventions (NPIs); vaporized hydrogen peroxide (VH202); Emergency Use Authorization (EUA); Healthcare workers (HCWs).

pace with sustaining and disruptive practices in surgery for healthcare applications. Leading sterilization companies in partnership with universities are also developing and deploying state-of-the-art biotechnology tools such as flow-cytometry to unlock real-time microbial inactivation where such approaches may supplement conventional plate counts (McEvoy et al., 2021). Immersive (digital) technologies are also partnering with medtech companies for complex virtual training on specific technical operations. For example, Mersus Technology (Immersive) has partnered with Boston Scientific to test and apply an "Avatar Academy Program that uses computer gaming to recreate virtual laboratories and cleanrooms, allowing medtech employees to familiarize themselves remotely with a complex work environment and processes. This approach will potentially automate training where one could theoretically run six bespoke training sessions in one day that previously would have taken a month, and can be extrapolated to address the full production chain delivered in a virtual environment" (Westmeath Independent, 2020). There is a pressing interest in also ensuring the safe reprocessing of reusable medical devices in healthcare applications that are challenged by the presence of recalcitrant biofilms harboring pathogenic microorganisms where failure to effectively clean, reprocess and sterilize may lead to significant patient risk.

HCWs have been in the constant face of COVID-19 for over two years where anxiety and stress can lead to mental health issues (Peteet, 2020); thus, highlighting the importance of maintaining effective disease prevention and control measures (Vaira et al., 2020). Peteet (2020) reported growing concerns about anxiety with COVID-19 that have led to recommendations for effective staff care, and greater availability of mental health treatment. This researcher has also noted existential concerns raised by the pandemic suggesting the importance of religious resources, as seen in research into patients dealing with advanced cancer. Many Asian countries introduced tougher COVID-19 restrictions compared to other countries which caused elevated levels of stress, anxiety and isolation. A-Singapore-based "Intellect" company recently raised $20 m to develop and manage a mobile phone app that regularly checks on users' moods with connectivity to exercise and recovery sessions and to therapists for real-time interventions (Cheung and Ripley, 2022).

8. Future recommendations, research and enterprise opportunities

- Identify and invest in appropriate scalable decontamination technologies that can effectively treat large volumes of used PPE during the COVID-19 pandemic with a view to recovery, reusing and recycling that will drive a long-term sustainable waste management system.
- Harmonize pandemic response plans (disease mitigation, preparation, response and recovery phases) including infrastructure, living labs etc. that facilitate opportunities to test, verify and validate point-of-use decontamination technologies for medical devices (including 3D printing) in healthcare, which also makes provision for ongoing and future pandemics where PPE (FFRs) may require reuse under EUA conditions.
- Promoter greater engagement of OEMS, sterilization companies with academic institutions, new businesses, policymakers and civil society, such as through Quintuple Helix Hub framework to inform new green solutions, such as the expansion of Rowan and Casey (2021). An example is the efficacy of new medical devices comprising biodegradable materials from a life cycle assessment and 360 degree holistic thinking perspective that can be decontaminated without loss of functionality or biocompatibility.
- Develop and apply risk models and pathways for new businesses to help investment in entrepreneurial activities that include increased funding support for new sustainable green innovations.
- Develop further, more rapid methods in microbiology to meet the need for real-time monitoring, sustainability and diversification including "Industry 5.0" human-centric models (Rowan et al., 2022).
- Greater interface between broad users (including academia, SMEs, MNCs) and policymakers/regulators to understand policies and standards for developing innovations and processes. MNCs in medtech and connected sterilization already very effectively communicate regulators at important policy interface.
- Increased education and training for greater engagement with multi actors including social sciences, humanities and communities for feedback on pandemic response and innovations.
- Promotion of open access publications and pandemic data hubs (such as Guidotti and Adria, 2020).
- Development of regional spatial and economic strategies to support the co-creation and development of innovations for the medtech sector in partnership with academia that also addresses circular bioeconomy opportunities, and digital transformation.
- Increased multi-disciplinary role of blending Science, Technology, Engineering and Mathematics (STEM) with Arts, Humanities and Social Sciences (AHSS), and industry for solutions.
- Greater research and provision of appropriate tailored support and intervention services for HCWs suffering from stress, anxiety and mental health as a result of meeting this pandemic response for society.
- Reflect to ensure effective communication and dissemination channels, messaging and timing to inform all stakeholders in society.
- Develop appropriate sustainability tools to assist SMEs, start-ups and entrepreneurs in the creation of a new medical device that addresses the life cycle from discovery to validation and addresses technology, society and policy readiness levels. This will de-risk investment and create local employment and regional development.
- Nurture and train a talent pool of high-caliber researchers for these and future applications.
- Resource regional pandemic response hubs that address a critical supply chain for PPE linked to education and outreach, which also includes digital transformation and sustainability along with disease prevention and control.
- Effective clinical waste management balanced with environmental protection and natural capital.
- Develop and introduce immersive technologies (digital) to address important practices in disease prevention and control from a training and education perspective.
- Digital transformation of PPE supply chain from EUA perspective such as using blockchain and AI.

Consent for publication

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CRediT authorship contribution statement

The author solely designed and wrote this paper.

Data availability

Data will be made available on request.

Declaration of competing interest

The author declares no conflict of interest.

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