Journal of Material Cycles and Waste Management (2023) 25:835–850
https://doi.org/10.1007/s10163-022-01563-x

ORIGINAL ARTICLE

Analysis of COVID-19 waste management in Vietnam and recommendations to adapt to the 'new normal' period

Trang D. T. Nguyen[1] · Toyohiko Nakakubo[1] · Kosuke Kawai[2]

Received: 15 July 2022 / Accepted: 27 November 2022 / Published online: 8 December 2022

Abstract

Amid the 4th wave of COVID-19, Vietnam reopened its economy, which placed extra burdens on the COVID-19 waste management system. This study analyzed existing issues and recommended adaptations to secure appropriate management of COVID-19 waste under the 'new normal' pandemic period. Results showed changes in COVID-19 waste characteristics (e.g., rapid rise in waste generation, lower percentage of plastic) and multiple other issues (e.g., presence of COVID-19 waste in municipal waste, lack of temporary storage sites and local treatment capacity), along with greater waste-handling responsibilities placed on authorities and higher infection risks. To adapt to the 'new normal', introduction of separate handling routes and collaboration in waste treatment were recommended. Employing the network of pharmacies used for vaccination would require COVID-19 waste collection from scattered, small-scale sources as part of the waste management solution. Also, following the 4R initiatives (reduce, reuse, recycle, recovery) could help ease the burden on the country's waste system and provide additional opportunities to move towards a circular economy in the post-acute COVID-19 era. The findings should contribute to a safer co-existence with the virus through appropriate waste management in Vietnam and could be used to tackle waste problems in other developing countries.

Keywords COVID-19 · Medical waste · Waste management · Adaptation · Developing country

Abbreviations

ADB	: Asian Development Bank
CEID	: Center for Environmental Information and Data (under VEA-MONRE)
COVID-19	: Coronavirus disease 2019
DONRE	: Department of Natural Resources and Environment (under the Provincial People's Committee)
HMW	: Hazardous medical waste
ICU	: Intensive care unit
MOH	: Ministry of Health
MONRE	: Ministry of Natural Resources and Environment
NSC	: National Steering Committee
PPE	: Personal protective equipment
qRT-PCR	: Real-time reverse-transcription polymerase chain reaction
URENCO	: Urban Environment Company
VEA	: Vietnam Environment Administration (under MONRE)
VIHEMA	: Vietnam Health Environment Management Agency (under MOH)
WHO	: World Health Organization

Introduction

The global pandemic of 'Coronavirus disease 2019' (COVID-19) caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) remains an acute crisis in 2022 [1], with ongoing significant worldwide spikes of infections driven by the highly transmissible Omicron variant—the dominant variant since March 2022 [1, 2]. Several countries are, however, gradually lifting their social restrictions to reopen their economies [1, 3], and entering a so-called 'new normal' period under which a pathway of 'co-existence with the virus' is replacing previous zero-COVID policies [3–5]. Countermeasures and preparedness to adapt

✉ Trang D. T. Nguyen
nguyen.thi.doan.trang@ocha.ac.jp

[1] Ochanomizu University, 2-1-1 Otsuka, Bunkyo, Tokyo 112-8610, Japan

[2] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

to such changes in overall crisis responses are required for waste management systems, which are, in addition to the healthcare system, essential in this era of COVID [1].

Waste management systems have struggled remarkably during the pandemic, mainly because of the increased generation of waste associated with COVID-19 [1, 3, 6–8]. The burden has been greater in developing countries where most of the waste management systems were not designed to operate under a crisis or are operating with limited resources or both [9–16]. Various issues emerged under pandemic time included unseparated COVID-19 waste in general waste [17–22], suspension of recycling [23, 24] and shortage of incineration capacity [15, 16, 25]. Furthermore, problems such as insufficient protective equipment for waste handlers [21, 26]; infections due to virus-laden waste to community [24], scavengers [19, 27] and waste handlers [20–22] added difficulties on the management of COVID-19 waste in those nations. Plastic pollution due to huge amount of discarded single-use personal protective equipment (PPE) was considered as the typical environmental consequence linking to the pandemic [1, 6], affecting air quality (from incineration), fresh water, oceans and threatening the marine life [28, 29]. The transition to 'new normal' pandemic conditions, which is viewed as necessary to help economies recover in several developing countries [4, 30, 31], likely presents additional waste management challenges, especially when all social restrictions have been lifted. A more environmentally sustainable model of waste management is thus required to gain the flexibility and adaptability of the current waste systems in the new situations of COVID crisis.

For future perspective, the move towards a circular economy was proposed for a probably more sustainable model of waste management in adaptation to post-COVID conditions [27, 32–35]. Incorporating 4R initiatives (reduce, reuse, recycling, recovery) into waste management strategy was likely a prerequisite approach [29, 33, 36] to mitigate the environmental consequences linked to pandemic and to shape a safer, more environmentally sustainable model for COVID-19 waste management in the pathway towards circular economy. Initiatives of 4Rs aimed at lessening the exploitation of resources (reduce), extending the lifespan of the products through possibly multiple usage (reuse), considering waste as resources for reprocessed products, materials, substances whether for the original or other purposes (recycling), or for usable energy, heat (recovery). Because of its infectiousness, reprocessing of COVID-19 waste is complex for disinfecting and converting the materials and thus, in most of the cases, is recognized under a category of both recycling and recovery. Opportunities and options for 4Rs have been identified for COVID-19 waste in recent literature [29, 36–40]. In addition, the World Health Organization (WHO) introduced options on reduction and reuse of COVID-19 waste to cope with plastic pollution that have been intensified due to the mass generation of discarded PPE and other COVID-19 related waste [6]. Appropriate recommendations to address the current issues and to adapt to new challenges in this new phase of the pandemic are therefore vital, particularly in developing nations, in the fight against COVID-19 through waste management.

Since the onset of the pandemic in late January 2020, Vietnam saw a steep surge in infections under the 4th wave of infections since April 2021, driven by the highly contagious Delta variant and additionally by Omicron since December 2021. Several strict antivirus measures were accordingly introduced to curb the outbreak, including complete social restrictions such as a nearly 3-month lockdown imposed at the epicenter of Ho Chi Minh City. Soon after the pandemic had first been brought under control nationwide, Vietnam adopted a new pandemic response policy of 'safe adaptation, flexible and effective control of the COVID-19 pandemic' (Resolution 128, Resolution 128/NQ-CP, 11 October 2021) to restore the economy while also introducing flexible responses against the highly transmissible Omicron variant without large-scale social restrictions [5, 41]. In terms of management of waste associated with COVID-19, the Ministry of Health (MOH) stressed the need for suitable countermeasures and preparedness in adaptation to a new pandemic period, which had a high probability of another surge in infections when all of the social restrictions had been lifted due to newly-found subvariants and other variants of concern [42]. Also, the newly-launched *Pandemic prevention and control program for 2022–2023* (Resolution 38, 17 March 2022) confirmed the requirement of adaptive management of waste in the 'new normal' period.

Operating under crisis conditions which it had no prior experience, the waste management system in the country was burdened with a much larger than normal amount of waste generated. According to *Law on prevention and control of infectious diseases* (Law 03/2007/QH12), resources (e.g., medicines, chemicals) and equipment (e.g., medical equipment, PPE) needed for combating COVID-19, a declared national pandemic, were fully supplied by the authorities. In the absence of reported data, generation and composition of COVID-19 waste were estimated from the used amounts and typical compositions of the supplied resources, equipment [43]. Estimated amount of 1486 t of COVID-19 generated in the first year of the pandemic caused the annual rate of increase of hazardous medical waste generation to have nearly doubled [43], but infrastructure resources remained limited [44–46]. Other issues (e.g., overwhelmed local treatment capacity, shortage of waste handlers) also remained inadequately addressed [47]. In the absence of social restrictions under the 'new normal' period, these issues could be exacerbated. Understanding waste management under pandemic conditions in general as well as grasping specific issues in particular is critical to improving

the performance of the existing waste treatment system and supporting preparedness for the 'new normal'. However, little was found in a literature search on the management of waste associated with COVID-19 in Vietnam: Nguyen et al. estimated COVID-19 waste generation and composition in the country during the first year under complete restrictions [43] and assessed the treatment capacities of COVID-19 waste nationwide, in the epicenter of Ho Chi Minh City during the 4th (Delta) wave [48], the Asian Development Bank (ADB) projected the additional amount of COVID-19 waste for Hanoi using China's experience [13], and Le et al. proposed a decentralized blockchain-based system for automating waste treatment processes for medical equipment and supplies after usage among relevant parties [49]. A comprehensive analysis of COVID-19 waste practices and issues considering the changes in pandemic response policy in the country was therefore essential to improve the performances of the country's waste system and to adapt to the new phase of this unprecedented crisis.

This study analyzed the management practices related to waste associated with COVID-19 in Vietnam to address current issues and to prepare recommendations to adapt to the 'new normal' period, so as to secure the correct management of COVID-19 waste. The recommendations provide a timely contribution in accordance with the legal recognition of the need for a pandemic response strategy for a safe coexistence with the virus under the ongoing pandemic. The findings could also serve as a practical country-based reference for other developing nations to tackle their own waste problems because the end of the COVID-19 pandemic is not currently in sight.

Sources of COVID-19 waste generation in the 'new normal' period

Sources of COVID-19 waste generation, previously identified based on a monitoring and treatment scheme [43], were updated in association with the adjusted policy of pandemic response in 'new normal' (Fig. 1). Because movement was being made away from a target of 'new case control' under the former zero-COVID policy, mandatory quarantine was

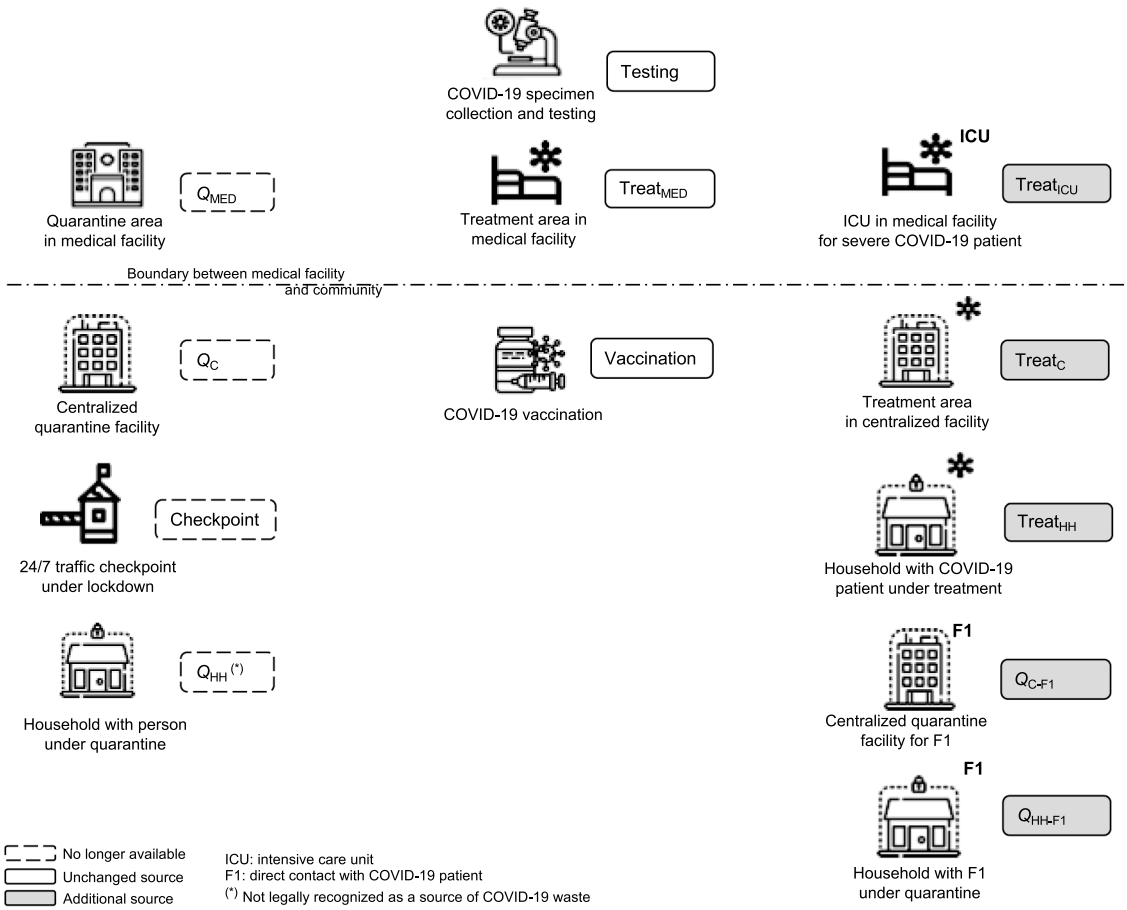

Fig. 1 Changes in sources of COVID-19 waste generation in the transition to 'new normal' period; name of source is under the symbol and its abbreviation is bordered, placed in the right of symbol

removed for a number of targeted persons and no lockdown would be imposed in 'new normal' period. As a result, 4 sources of COVID-19 waste generation included in the previous scheme were no longer included during the 'new normal' period. These were sources of waste from quarantine areas (medical facilities, Q_{MED}; centralized quarantine facilities, Q_C; households, Q_{HH}) and from 24/7 traffic checkpoints under lockdown (Checkpoint). Similarly, following the target of 'severe case control' currently in place, 5 more sources of COVID-19 waste were added according to the changed scheme of monitoring and treatment in 'new normal'. Of the 5 added sources, 3 were treatment areas for F0 (i.e., COVID-19 patients: intensive care unit, $Treat_{ICU}$; centralized facility, $Treat_C$; households, $Treat_{HH}$) linking to the newly-adopted classification of F0 by severity that was put in practice to improve the treatment efficiency and to protect the medical system from being collapsed due to excessive hospitalizations. Other 2 additional sources of waste were places out of medical facilities for F1 persons (i.e., those with direct contact with F0 persons: centralized facility, $Q_{C\text{-}F1}$; households, $Q_{HH\text{-}F1}$) as a solution to secure hospital beds for F0 persons. Three sources were unchanged over the shifting to 'new normal' including COVID-19 specimen collection and testing, Testing; treatment areas in medical facilities, $Treat_{MED}$; and COVID-19 vaccination, Vaccination. For convenience, we refer to these by their corresponding abbreviations; for example, Testing refers to 'COVID-19 specimen collection and testing' (Fig. 1).

In this study, estimation of COVID-19 waste generation in April 2020–March 2022 covered all sources in Fig. 1 according to their specified availability during calculation period. Q_{HH} was excluded because it was not recognized as a source of COVID-19 waste (Decision 3455). The 'new normal' waste management scheme as of March 2022 included sources available at this time (5 additional, 3 unchanged sources; Fig. 1). However, the recommendations proposed in this study omit $Q_{C\text{-}F1}$ and $Q_{HH\text{-}F1}$ because F1 persons were no longer required to quarantine at centralized facilities or to self-isolate at households after April 2022 (Legal document 1909).

Materials and methods

Research framework

Based on the adopted regulations and estimation of COVID-19 waste characteristics (generation, composition), waste management practices were analyzed not only considering issues under complete restriction but also considering those that probably will occur under the 'new normal', as well as the influence of changes in regulations regarding the pandemic response. Conditions of pre-pandemic waste system was taken into account for a local-specified analysis results. Adaptive recommendations were accordingly proposed for a safer and more sustainable management of COVID-19 waste towards circular economy (Fig. 2). Analysis results were presented by stage in waste system (separation and collection, transportation, treatment), followed by proposed recommendations addressing the identified issues in 'new normal' in Results and discussion section.

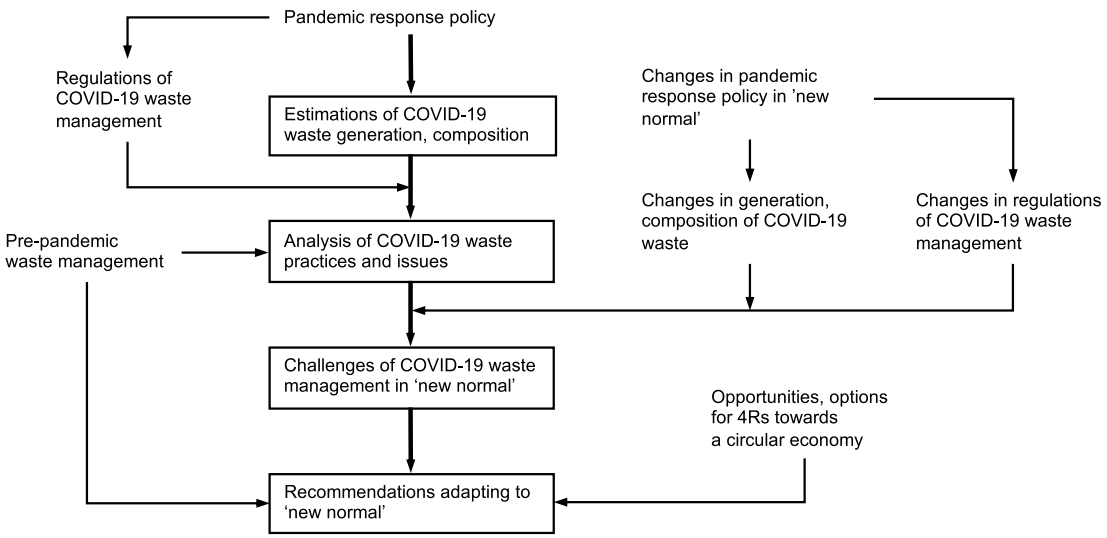

Fig. 2 Research framework

Estimations of COVID-19 waste generation, composition

Because of the absence of reported waste data, COVID-19 waste generation and composition were estimated from the state-supplied anti-pandemic resources (e.g., medicines, chemicals) and equipment (e.g., medical, personal protective), a method proposed for Vietnam [43], for the 2 years from April 2020 to March 2022 (i.e., since COVID-19 was declared a national pandemic). Employing the same method of estimation as the previous study enabled a comparison between the results in the present study that covered the transition into the 'new normal' period and those calculated only for the first year of the study period when the country was under complete social restrictions (April 2020–March 2021) [43].

COVID-19 waste generation was the total of all sources (i: Testing; $\text{Treat}_{\text{MED}}$; $\text{Treat}_{\text{ICU}}$; Treat_{C}; Treat_{HH}; Vaccination; Q_{MED}; Q_{C}). COVID-19 waste generation by source i (W_{i}) was calculated from the number of generating units (N_{i}) and the waste generation rate (R_{i}) calculated from the state supply of pandemic resources and equipment, estimated here as:

$W_{\text{i}} = \left(N_{\text{i}} * R_{\text{i}}\right)/1000$ [43]

Daily logged COVID-19 data were used as number of generating units (N_{i}) to estimate waste generation; they were acquired from the COVID-19 Information Portal of MOH (https://covid19.gov.vn/) and included the number of COVID-19 patients under treatment by place (ICU, medical facility, centralized facility, household), number of quarantined persons by place (medical facility, centralized facility), and number of real-time reverse-transcription polymerase chain reaction (qRT-PCR) tests performed and COVID-19 vaccination shots administered. Rates of waste generation (R_{i}) were additionally estimated for the 5 newly-identified sources of COVID-19 waste ($\text{Treat}_{\text{ICU}}$, Treat_{C}, Treat_{HH}, $Q_{\text{C-F1}}$, and $Q_{\text{HH-F1}}$) under 'new normal'. Rates of sources identified under complete restriction (Testing, $\text{Treat}_{\text{MED}}$, Vaccination, Q_{MED}, Q_{C}) were obtained from the previous study by Nguyen et al. [43]. Daily discharged amount of solid waste per medical bed and per habitant were referred to in reported data in the National Environment Reports of 2011 and 2019, respectively, and included as part of the estimate of the generation of COVID-19 waste for $\text{Treat}_{\text{ICU}}$ and Treat_{HH}. For estimating composition, the main materials of PPE components were acquired from a study by Purnomo et al. [40] and product specifications on www.amazon.co.jp, in addition to compositions of clinic waste by UNEP-IETC [50] and of municipal waste by the World Bank [51]. The quantities of state-supplied anti-pandemic resources and equipment used in the estimation of generation rates of COVID-19 waste are presented in Supplementary Table S1.

Sources of data and information

The volume of hazardous medical waste generated before the pandemic was acquired from official sources (Center for Environmental Information and Data, under the Vietnam Environment Administration (VEA)–MONRE, http://ceid.gov.vn/; Statistical Reporting System, http://thongke.monre.gov.vn/), as well as from environmental reports and other sources. Estimates of waste generation in the non-COVID scenario was based on the reported annual rate of increase in waste generation of 7.6% [46] and using the reported value of 21,810 t of waste in 2019 [52]. Descriptions of all types of waste mentioned in this study are presented in Supplementary Table S2.

Legal documents on pandemic responses and reports related to waste management by WHO, National Steering Committee (NSC), MOH, Ministry of Natural Resources and Environment (MONRE), and the WHO Representative Office in Vietnam were thoroughly reviewed to gain a comprehensive understanding of the hazardous medical waste management system before and during the pandemic. Approved waste management planning prior to the pandemic and relevant information following the *Program on COVID-19 prevention and control for 2022–2023* (Resolution 38) provided necessary background on a prospective view of the 'new normal' under which handling of COVID-19 waste would be performed.

Conditions for calculation

The estimates are considered to be reliable in part because of the ready availability of COVID-19 data from official source (MOH), as well as the availability of actual quantities of resources and equipment supplied to combat the pandemic. Changes in regulations on pandemic control during the calculation period and on availability of reported COVID data (Table 1), however, influenced the estimation. Exceptions of estimation of COVID-19 waste generation from $Q_{\text{C-F1}}$ and $Q_{\text{HH-F1}}$ were considered to be acceptable owing to their small rates of daily waste generation (of 47.35 and 24.62 g per bed, respectively) and the lack of reported data on their generating units. Further exception was made for estimation of COVID-19 waste generation from Checkpoint because of its partial availability during lockdown. In the absence of waste collection rates, all waste generated was assumed to be eventually collected for treatment. Testing was considered to be a source of COVID-19 waste generation within medical facilities, given that 331 of the 334 qualified laboratories nationwide performing COVID-19 qPCR testing were located in MOH hospitals and provincial Centers for Disease Control and Prevention, and the remaining 3 were directed by other ministries [5]. Also, Vaccination was seen as a community source because almost all COVID-19 vaccines were

Table 1 Availability of sources of COVID-19 waste generation according to reported COVID-19 data; months in italic indicate 'new normal' period (Data source: MOH)

Source of waste	Availability of source																							
Year	2020									2021												2022		
Month	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	*10*	*11*	*12*	*1*	*2*	*3*
	Year 1												Year 2											
Testing																								
$Treat_{MED}$																								
$Treat_{ICU}$																								
$Treat_{C}$																								
$Treat_{HH}$																								
Vaccination																								
Q_{MED}																								
Q_{C}																								

administered in numerous temporary vaccine clinics in the community as part of the nationwide mass vaccination program [5] except for a relatively few delivered in medical facilities for staff members.

Results and discussion

Waste identification and management regulations

Legally recognized under the term 'potentially SARS-CoV-2 contaminated waste', COVID-19 waste was classified as infectious waste, a subcategory of hazardous medical waste, and was co-administered by MOH and MONRE, according to Decision 3455/QD-BCDQG (Decision 3455, 5 August 2020) and Legal document 102/MT-YT (Legal document 102, 4 March 2021). All legal documents in relation to COVID-19 waste management mentioned in this study are presented in Supplementary Table S3. Management of COVID-19 waste was subjected to regulations on medical waste management within medical facilities and on hazardous waste management (Circular 20 and Circular 02), which replaced their previous versions (Joint Circular 58 and Circular 36) to become the basis for Decision 3455. Resources (e.g., medicines, chemicals) and equipment (e.g., medical equipment, PPE) for combating the pandemic were fully supplied by authorities following the Law 03/2007/QH12 (Law 03, 21 November 2007) as COVID-19 was declared a national pandemic (Decision 447, 1 April 2020).

Waste handling responsibility

Responsibility for COVID-19 waste handling varied by source. Medical facilities are required to manage the waste produced within their boundaries, including that from COVID-19 testing laboratories and from treatment and quarantine areas (Testing, $Treat_{ICU}$, $Treat_{MED}$ and Q_{MED}; Fig. 1) (Circular 20). Operating under the direction of the local authority, or the Provincial People's Committee, the state-run Urban Environment Company (URENCO) was responsible for handling of COVID-19 waste from the remaining sources ($Treat_{C}$, $Treat_{HH}$, Q_{C}, $Q_{C\text{-}F1}$, $Q_{HH\text{-}F1}$, Checkpoint and Vaccination; Fig. 1) using its current system of management for hazardous medical waste (Circular 02). Because it was not officially recognized as COVID-19 waste, medical waste from households with a person or persons under quarantine (Q_{HH}) followed the current handling flow of municipal solid waste. The new flexible antivirus measures in the 'new normal' were reflected in changes in the sources of COVID-19 waste generation (Fig. 1); this required a reallocation of some of the F0 sources and all F1 sources from medical facilities to the community (Fig. 3) and careful consideration of proper management of COVID-19 waste in the community to prevent infections related to contaminated waste. As a result, greater responsibility was placed on local communities (i.e., the people's committees) in the handling of COVID-19 waste. Private companies licensed to treat hazardous medical waste were encouraged to join URENCO in COVID-19 waste treatment (Decision 3455) in addition to their usual provision of treatment services to medical facilities lacking incinerators.

Estimated generation and composition

An estimated 279,137 t of COVID-19 waste was produced over the 2 study years (Table 2), an average of approximately 11,630 t per month, or nearly 383 t per day. Households with COVID-19 patients under treatment ($Treat_{HH}$) generated the largest amount (130,605 t; 47%), despite the fact that the category was only available for 4 of the 24 study months. The large amount of household waste was influenced by the great number of mild and asymptomatic COVID-19 patients who recuperated in their homes because the Omicron variant caused less severe symptoms than previous variants of SARS-CoV-2 [2, 5]. Moreover, COVID-19 waste production fluctuated largely during the study period (Fig. 4); the maximum monthly amount (101,042 t), far greater than the average value, apparently stretched the treatment capacity

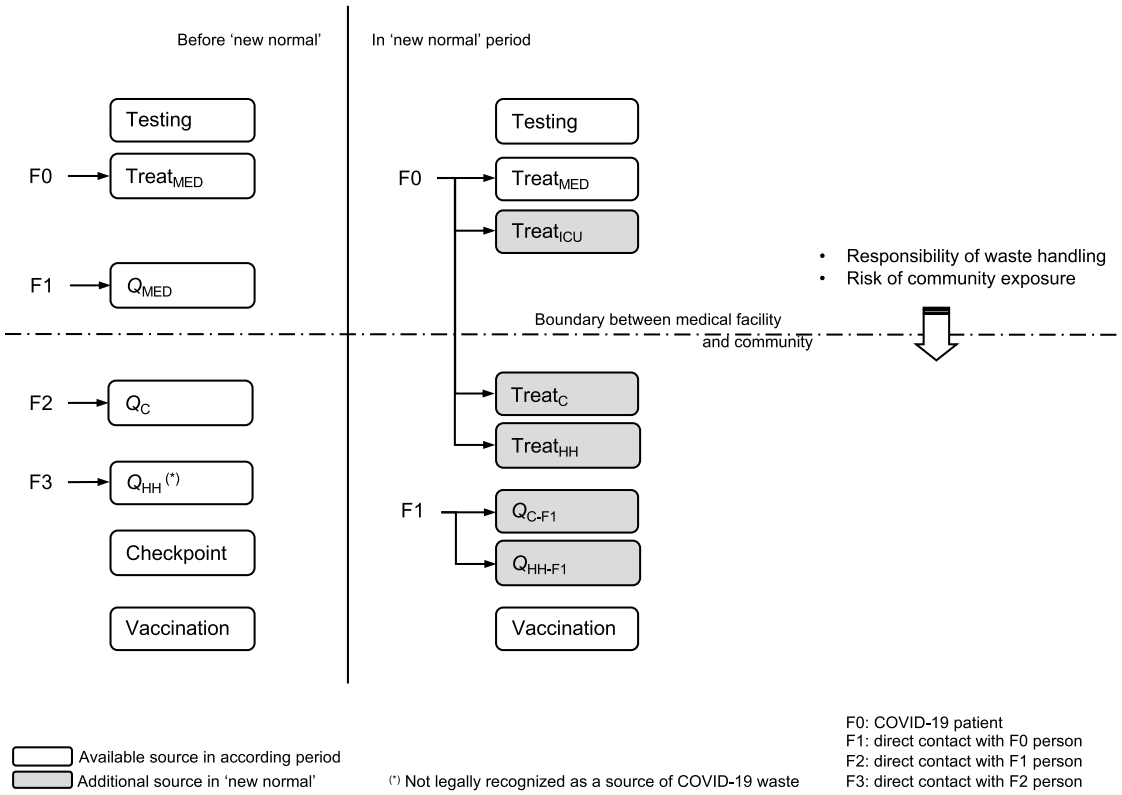

Fig. 3 Transition of waste-handling responsibilities and community exposure following the reallocation of sources of COVID-19 waste generation in the 'new normal' period

Table 2 Generation rates and volume of COVID-19 waste (April 2020–March 2022)

Source of waste	Rate of waste generation		Estimated generation of waste	
			t (2 years)$^{-1}$	(%)
Testing	50	g test^{-1}	2273.8	0.8
Treat$_{MED}$	3.86	kg bed^{-1} day^{-1}	130,275.5	46.7
Treat$_{ICU}$	4.64	kg bed^{-1} day^{-1}	5008.7	1.8
Treat$_C$	3.09	kg bed^{-1} day^{-1}	2674.7	1.0
Treat$_{HH}$	1.94	kg bed^{-1} day^{-1}	130,605.0	46.8
Vaccination	29.89	g shot^{-1}	6168.2	2.2
Q_{MED}	3.86	kg bed^{-1} day^{-1}	1694.6	0.6
Q_C	46.43	g bed^{-1} day^{-1}	436.1	0.2
Total			279,136.6	100.0

of the existing system. In general, growth of estimated generation of COVID-19 waste was found in correlation with pandemic progression during study period. The large and sudden growth of COVID-19 waste generation in March 2022 was probably a result of the surge associated with the Omicron variant, which became dominant nationwide in February 2022 [5, 53]. The increase in waste generation by community sources (Fig. 4) affirmed the heavier responsibility of local authorities in COVID-19 waste handling at this time.

We compared the amount of waste generated during the study period with that projected for the same period in a non-COVID scenario. The pandemic clearly caused significant growth in hazardous medical waste generation (Fig. 5) and consequently placed remarkable burdens on the nation's existing waste-handling infrastructure. Under these conditions, any system would most likely be overwhelmed as the demand for waste treatment in a timely manner as is required for infectious waste surpassed the available treatment capacity.

Plastic accounted for nearly 54% of the total COVID-19 waste composition (Fig. 6). The 'other' category of constituents expanded to 36.2% in the second year from its previous proportion of just 0.6%. The changes in waste composition were probably influenced by the addition of municipal solid waste by COVID-19 patients, identified as COVID-19 waste, in the connection with the steep surge in infections during December 2021–March 2022. The composition is important because the treatment efficiency of COVID-19 waste by incineration would be affected if a larger share of municipal solid waste containing a higher level of moisture and having

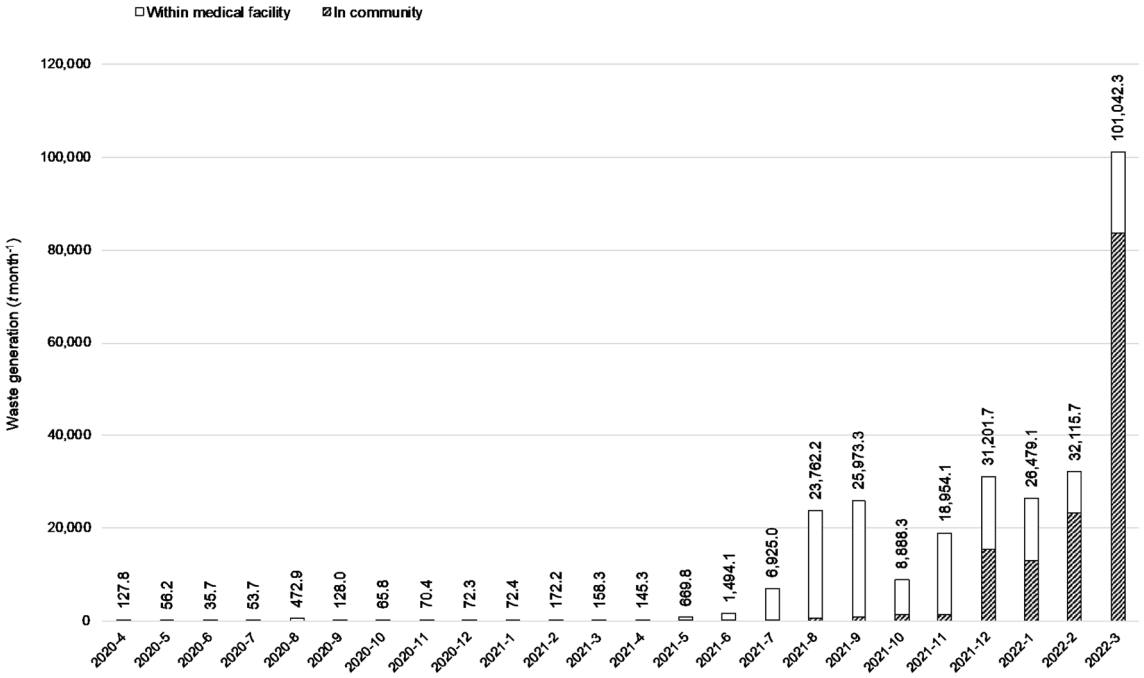

Fig. 4 Estimated monthly distribution of the amount of COVID-19 waste generated (April 2020–March 2022)

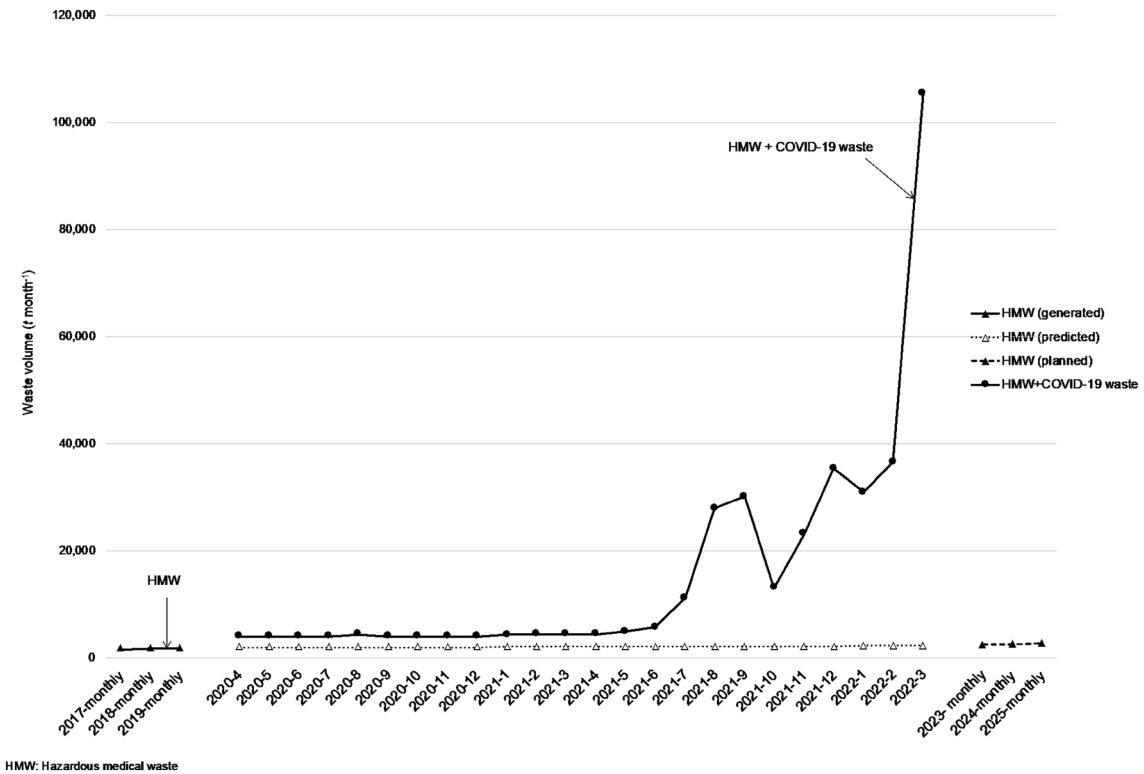

Fig. 5 Generation of hazardous medical waste under COVID-19 and a non-COVID scenario

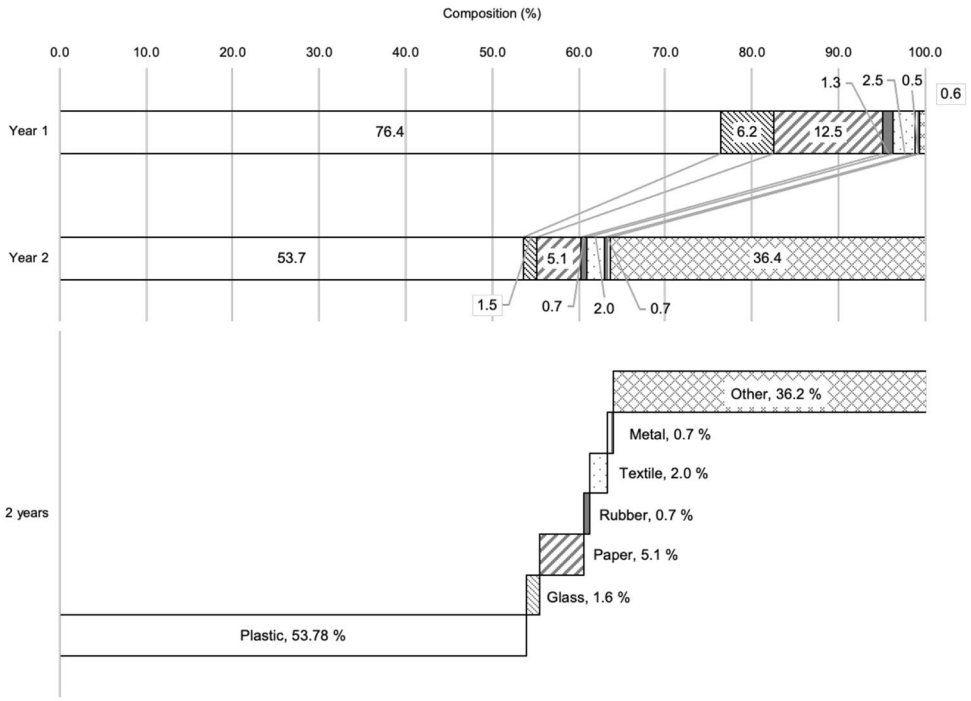

Fig. 6 Changes in estimated composition of COVID-19 waste (April 2020–March 2022)

a much lower energy value [50] was included in the feedstock. The monthly estimated compositions of COVID-19 waste are presented in Supplementary Fig. S1.

Management practices and issues

Separation and collection

Separation and collection of COVID-19 waste varied depending on the source (Fig. 7); the procedures were governed by regulations in Decision 3455 by NSC; Circular 02, Legal document 1336 by MONRE; Circular 20, Legal documents 1560, 922, 5599, and 5679 by MOH, and Legal document 102 by VIHEMA-MOH (Table S3). All of the discharged waste from sources with COVID-19 patients under treatment (in medical and centralized facilities and households) was collected as infectious waste (COVID-19 waste) and handled separately. In quarantine areas (in centralized facilities and households), only discharged medical waste was collected as COVID-19 waste, except for areas within a medical facility, where both medical and municipal waste were treated as COVID-19 waste. Medical waste from COVID-19 testing and vaccination was separated for handling as COVID-19 waste. Moreover, medical waste consisting of used PPE clothing, gloves, and masks from lockdown areas (e.g., from staff at checkpoints) was also identified as 'potentially SARS-CoV-2 contaminated waste' and handled as COVID-19 waste.

COVID-19 waste was regulated to be packed, sealed in yellow standard bags, and labeled as 'potentially SARS-CoV-2 contaminated waste' before transportation for final disposal. This requirement distinguished COVID-19 waste from other medical waste discharged within medical facilities, which is also packed in yellow bags, and from municipal waste (in green bags) for handling priority. Labeling was also required for waste bins that were placed by the front doors of F0 households ($Treat_{HH}$); they were dedicated for PPE disposal by visiting medical staff. Provision of yellow standard bags dedicated for infectious waste from community sources was prioritized for centralized waste generators (e.g., $Treat_C$, Vaccination) but not for the great number of scattered generation units such as $Treat_{HH}$. Waste from laboratories performing qRT-PCR testing (Testing) was identified as highly infectious waste (Decision 3455) and had to be pre-treated in an autoclave before being mixed with other infectious waste in medical facilities for collection. Waste from vaccination was categorized as sharp waste (e.g., disposed auto-disable syringes) and medical waste (e.g., used PPE) and packed and labeled in safety boxes and yellow bags, respectively. Unused vials of vaccines were returned to manufacturers or disposed of following the established procedure for pharmaceutical goods (Legal document 5679). This waste was not part of the COVID-19 waste flow.

Although it was categorized as potentially SARS-CoV-2 contaminated waste, $Treat_{HH}$ waste was found mixed in with municipal solid waste [47]. This waste would have gone

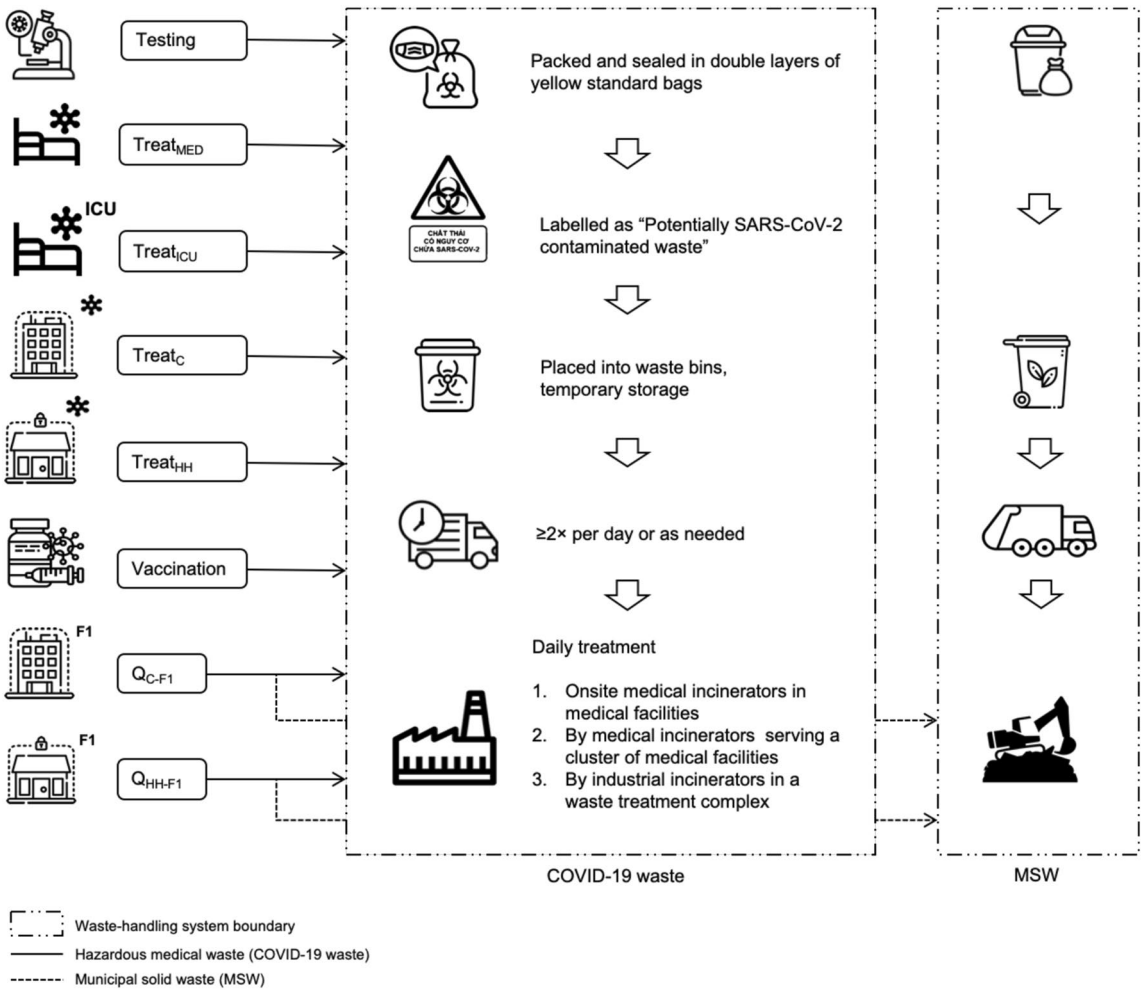

Fig. 7 Management scheme of COVID-19 waste by March 2022

through the normal waste-handling steps before most likely ending up in a landfill, the destination of 71% of all municipal waste [54]; other forms of treatment include composting and incineration. In addition to at-source separation awareness, a shortage of waste handlers, transportation vehicles and funding were typical constraints to the introduction of additional collection and transportation for household COVID-19 waste, which operated independent of the current municipal waste system. COVID-19 households were numerous and scattered widely in the community. The additional time, labor, and suitable vehicles needed to collect this waste resulted in delays in collection and transportation and slowed the process of isolating potentially contaminated waste from the community, which is a prerequisite for infection control.

Transportation

Transportation of COVID-19 waste took place on a daily basis for infection prevention. It sometimes was more frequent in accordance with demand and the availability of vehicles specialized for use with infectious waste. In the face of a rapidly growing amount of waste, authorities allowed COVID-19 waste to be stored temporarily in hazardous waste storage sites in medical facilities. Because these were designed for non-crisis conditions, available storage space was most likely insufficient for COVID-19 waste storage. Moreover, there was a lack of temporary storage sites for COVID-19 waste discharged by community sources, which raised the risk of infection associated with contaminated waste. Furthermore, some infectious waste remained uncollected for timely disposal because of the previously noted

shortage of waste handlers and the sometimes-heavy workloads, which also highlights the need for temporary sites for COVID-19 waste storage.

Waste handlers in the formal waste management sector (e.g., URENCO) and medical facilities were provided with adequate PPE (PPE level 3: medical mask, gloves, PPE clothing, shoe covers, face shields) for safety during collection, transportation, and treatment of COVID-19 waste (Decisions 4159, 1259). However, those working in the informal sector (e.g., waste collection service cooperatives) lacked such protective equipment because they were not responsible for COVID-19 waste handling and thus were not required to wear or provided with state-supplied PPE. Some informal workers wore their own protective equipment, however, usually medical or fabric masks, gloves, and a disposable raincoat. Given the presence of unsorted COVID-19 waste in municipal waste, the inadequate use of PPE could raise the potential risk of infection of informal waste handlers by contaminated waste, especially in the 'new normal' period.

Treatment

Incineration within a day of generation was required for safe, final disposal of COVID-19 waste, preferably in an onsite hazardous medical waste incinerator in medical facilities or in incinerators serving a cluster of medical facilities that did not have onsite incinerators. Incinerators used for industrial hazardous waste were also encouraged to accept COVID-19 waste in cases where the demand for treatment surpassed the available capacity of medical waste incinerators (Decision 3455, Legal document 1878). Flue gas must meet the emission standards in QCVN 02:2012/BTNMT. The pretreatment of waste from COVID-19 testing laboratories was handled according to guidelines in QCVN 55:2013/BTNMT (Table S3).

Vietnam is likely able to handle COVID-19 waste (hazardous medical waste) treatment using its enormous hazardous waste treatment capacity (1.3 million t per year) [46]. However, deficits in local capacity for waste treatment probably occurred when demand for waste treatment surpassed the capacity of the existing disposal infrastructure; an example of this occurred in Ho Chi Minh City, the epicenter of the 4th (Delta) wave during August–October 2021 [48, 55]. Furthermore, limited disposal infrastructure in remote and underdeveloped provinces or localities [44, 56] also contributed to difficulties in properly treating COVID-19 waste.

Most of identified issues in Vietnam were found similar to those in other developing countries, including presence of COVID-19 waste in municipal waste, a lack of temporary storage sites, and deficits in local capacity for COVID-19 waste treatment. However, inadequate PPE for waste handlers during COVID was mainly recognized in informal waste sector. In 'new normal' period of pandemic, those issues were likely to exacerbated as social restrictions were lifted.

Recommendations for adapting to the 'new normal'

To address current issues using existing resources for safer and more appropriate waste management practices in the transition to the 'new normal' period of the pandemic, we propose recommendations that cover all stages of solid waste management from at-source separation to final disposal (Fig. 7) and all sources of COVID-19 waste generation including testing, treatment, and vaccination during 'new normal' except for those of F1 ($Q_{\text{C-F1}}$ and $Q_{\text{HH-F1}}$; Fig. 1). They included separate handling route of COVID-19 waste for household COVID-19 waste, collaboration in waste treatment, adaptive collection of COVID-19 vaccination waste and enhancing COVID-19 waste characteristics.

Separate handling route of COVID-19 waste for household COVID-19 waste

Introduction of a separated handling route for COVID-19 waste discharged from Treat_{HH} appeared to address multiple issues in COVID-19 waste management practices and also to serve as a longer-term response in waste management following the promotion of home-based treatment of COVID-19 patients (Resolution 128). Stickers could be used as an alternative to yellow standard bags to deal with the shortage of yellow standard bags for household COVID-19 waste because the waste would still be distinguishable from municipal waste. The informal sector is a promising alternative to perform COVID-19 waste collection using its network of collection routes and suitable vehicles, many of which are able to perform door-to-door waste collection, even in narrow roads. Collection fees for COVID-19 waste should be determined by referring to Law 03 and other relevant regulations, taking into account the extra cost needed for safety and infection prevention (e.g., PPE for waste handlers, added antivirus measures) in addition to the cost to operate the collection network, under the direction of the local authority. In compliance with current standards for storing hazardous medical waste, temporary storage sites for the COVID-19 waste community could be positioned within the boundaries of district-level or ward-level medical centers that would be quite distant from the nearest households and accessible by trucks. COVID-19 waste collected by the informal sector

and moved to temporary storage sites could then be transported by the formal sector to final disposal sites using specialized vehicles. Furthermore, collection times and collection routes need to be rescheduled and reorganized in both the formal and informal sectors to optimize the collection of COVID-19 waste along with that of municipal solid waste, according to service areas and operational capabilities.

Collaboration in waste treatment

Collaboration in waste treatment, in principal authorized under Decision 3455, is likely an efficient way to tackle local deficiencies in treatment capacity for COVID-19 waste by employing the nation's available capacity and is also consistent with previous suggestions for developing countries in securing treatment capacity of pandemic-related waste [9]. This type of collaboration would expand the treatment capacity for COVID-19 waste by having private treatment service providers join URENCO. Under Delta outbreak (April–October 2021), capacity for COVID-19 waste treatment in Ho Chi Minh City was practically enhanced from 42 to 69 t per day, reducing the treatment occupancy rate—the ratio of estimated demand to calculated capacity—from 395.7 to 290.3% through waste treatment collaboration between 3 private treatment companies (Viet Uc Environment Joint Stock Company, Moc An Chau Logistics Corporation and Green Sai Gon Company) and the state-run Ho Chi Minh City Urban Environment Company Limited [48]. Considering the treatment demand on average during the outbreak (133.4 t per day, [48]), a total of 159 t in capacity per day had been planned to be available from 2022 over such the collaboration in waste treatment to secure the COVID-19 waste treatment in the city [55]. Joint treatment providers must be licensed to treat hazardous medical waste by incineration and satisfy requirements for treating a larger-than-usual amount of infectious waste (e.g., operating incinerators in a waste treatment complex, adopting necessary measures for infection prevention). Collaboration could be introduced within a province or region, depending on specific conditions of treatment capacity and demand. Adequate antivirus measures are essential for the safe transportation of a large amount of infectious waste, especially if it crosses provincial boundaries. Additionally, Global Positioning System/Geographical Information System technology should be used for tracking and managing the transportation of hazardous waste with the agreement of the relevant entities regarding information sharing. A thorough assessment of capacity of COVID-19 waste treatment is needed at both the local and regional levels for a ready and effective response in the context of the unpredictable progression of the pandemic.

Adaptive collection of COVID-19 vaccination waste

Before the 'new normal' period, public establishments (e.g., schools, sport centers, indoor stadiums) were temporarily repurposed for use as vaccination clinics under the national mass vaccination campaign. As these sites were restored to their original functions when restrictions were lifted, the national network of pharmacies was likely to be employed as a possible alternative for administering additional booster shots of COVID-19 vaccines, as well as for supplying approved COVID-19 treatment drugs. These actions would be taken in association with the promotion of home-based treatment of COVID-19 patients as part of a strategy to flexibly and effectively control COVID (Resolution 128). Hazardous waste from pharmacies—categorized as small-scale sources of hazardous medical waste—includes discharged chemicals and medicines containing hazardous substances, is characterized as poisonous waste, and is currently regulated to be collected on an on-demand basis in a composite or stainless-steel container with a 30–50 kg storage capacity installed behind the driver's seat of a motorcycle (Circular 20). Vaccination waste could also be collected using this convenient means of transportation with some added infection-prevention measures. The collection frequency and amount of temporary storage capacity should be increased accordingly to ensure the timely and safe handling of such infectious waste.

Enhancing COVID-19 waste characteristics

Since the beginning of the pandemic, to bring infections under control, Vietnam classified all waste that was potentially contaminated with SARS-CoV-2 as infectious waste (COVID-19 waste) based on the initial information available on the survival and possibility of transmission of the virus through solid waste. This determination resulted in a great increase in the amount of waste generated and subject to special handling. For example, for COVID-19 patients under treatment in medical facilities ($Treat_{MED}$) under the formerly complete restrictions, all wastes discharged, including both municipal waste and pandemic-induced waste (used PPE for patients, medical staff, and waste handlers; disposable medical care equipment and sterilization), were identified as COVID-19 waste (Decision 3455). This classification introduced an estimated daily amount of 4.64 kg per bed of infectious-identified waste to the existing waste system [43], far larger than a previously reported amount of 0.86 kg bed^{-1} day^{-1} in the absence of the pandemic [45]. Similar phenomena have been observed worldwide [6], although the WHO has stated that no change is needed in the classification of waste discharged by COVID-19 patients in terms of infectious and non-infectious waste [6, 57].

Table 3 Options for 4Rs implementation in COVID-19 waste [6, 29, 36–40, 58]; (*)indicates example of application in Vietnam

Option for 4Rs implementation		Examples
Reduce	Ensure the rational and appropriate use of PPE [6]	(*) Vaccinator should wear a medical mask (3 g, [58] instead of PPE level 2 (medical mask, protective clothing, medical gloves, face shield; 252 g, Decision 4159)
	Exclude municipal waste from infectious medical waste (COVID-19 waste) [6, 37, 39]	(*) Excluding the municipal waste discharged by patient and caregiver (1.08 and 0.54 kg per day, respectively) could cut the daily amount of COVID-19 waste from household with patient under treatment (TreatHH) from 1.94 to 0.32 kg per bed
	Smaller quantities for healthcare commodities and vaccine [6]	Individually packaging for sterile healthcare items only [6]
Reuse	Reuse of masks, gowns, or eye protectors with appropriate decontamination, sterilization processing [6, 29, 36]	Reuse of masks, gowns, or eye protectors after decontamination processing using dry heat, vaporized hydrogen peroxide, ozone, or Ultraviolet light [36]
Recycle, recovery	More sustainable packaging for vaccine [6, 38]	Replacement of conventional polypropylene based plastics with bioplastics or paper for vaccine packaging [38]
	Use of PPE made with greater proportion of renewable, bio-based or recyclable materials as an alternatives to single-use PPE items [29]	Biodegradable gloves made by polysaccharide-based material-filled natural rubber latex (PFNRL) [36]
		Cotton fabric face masks [36]
	Safety processing COVID-19 medical waste for energy and material recovery	Recycling of used medical masks for repurposing as construction materials [6]
		Safely convert COVID-19 related medical waste to a usable fuel or heat available with disinfection stage added or integrated with the selected technology [40]

As we learn more about the virus and its behaviors in the environment, better identification and classification of waste associated with COVID is needed with the goal of improving the 4Rs (reduce, reuse, recycle, recovery) in 'new normal', for example, using reusable, bio-based, or recyclable materials for PPE (e.g., face shields, goggles) and more sustainable and smaller amounts of packaging (e.g., for medical masks or vaccine shipments) [6]. This could help to reduce the volume of generated waste and improve the efficiency of incineration treatment, thereby easing the burden on the current waste system as well as moving towards the larger goal of a circular economy as it applies to waste in the post-acute COVID-19 period. Of options for 4Rs implementation (Table 3), 2 examples in Vietnam likely supported the application of 4Rs to enhance COVID-19 waste characteristics using 'reduce' initiative in particular. Further considerations were required to explore more potential applications, covering also other 4R initiatives.

Conclusion

The waste management system in Vietnam struggled during the pandemic because of the large and sudden growth in waste generation, growth that far exceeded that projected for a non-COVID scenario as well as that approved during planning. In our analysis of current waste management practices, we found a number of issues that constrained the proper management of COVID-19 waste and posed a higher risk of infection in relation to contaminated waste. These included mixing of COVID-19 waste in municipal waste, a lack of temporary storage sites for infectious waste, local deficits in waste treatment, and inadequate provision of PPE for waste handlers in the informal sector. As the "new normal" period of the pandemic was implemented, these issues appeared to be exacerbated as social restrictions were lifted. Furthermore, reallocation of part of the recognized sources of COVID-19 waste placed more responsibility for waste handling on local communities and caused a higher level of exposure risk to potentially contaminated waste. In addition, the composition of COVID-19 waste changed such that the proportion of plastic (which is highly combustible in incinerators) was reduced in the second year (including the "new normal"), as compared to the first year (under complete social restriction).

To secure the correct management of COVID-19 waste, a set of recommendations were prepared to address the current issues and those that would probably occur in the new normal period. Separate handling of home treatment COVID-19 waste is highly recommended to ensure the adequate isolation of infectious waste (COVID-19 waste) from the community to prevent additional infection, particularly because home-based treatment of COVID-19 patients is being

officially promoted in the 'new normal' period. To accomplish this task, the labor and infrastructure of the informal sector currently collecting household municipal waste are seen as suitable, but additional support will be needed for appropriate handling of household COVID-19 waste (e.g., PPE, stickers for COVID-19 waste bags). In addition, collaboration in waste treatment between URENCO and local private waste service providers is a promising route to secure additional capacity for treatment of COVID-19 waste. Pharmacies that administer booster shots of COVID-19 vaccines already have a collection system for hazardous waste, and this system could be modified with additional infection-prevention measures to also collect COVID-19 vaccination waste. Finally, better identification and classification of waste associated with COVID should be considered to enhance waste generation and composition to improve the 4Rs, with the aim of easing the burden on the current waste system and improving waste handling in the post-acute pandemic time.

The proposed recommendations should be considered in the context of regulations that are currently in place to combat the pandemic, as well as current management of solid waste in general and of COVID-19 waste in particular, and in consideration of longer-term strategies related to the pandemic response. Current measures should be maintained, but authorities should remain open to making any adjustments necessary to adapt to the complicated progression of the pandemic. These recommendations for COVID-19 waste management should be, along with those for the healthcare system, integrated into the overall planning of the COVID-19 response to enhance the efficiency of the responses and improve resilience against COVID. Other developing countries could use these findings and recommendations to tackle their waste management problems in the post-acute COVID period.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-022-01563-x.

Acknowledgements The authors thank the medical staff of the Immunology and Microbiology Department of the Pasteur Institute of Ho Chi Minh City for their valuable information on the Vietnamese system of the Centers for Disease Control and Prevention and on the roll-out planning of the 4th booster shot during the 'new normal' period of the national mass program on COVID-19 vaccination. We also thank the staff of Nguyen Dinh Chieu General Hospital in Ben Tre Province for information on the COVID-19 waste-handling system in a hospital dedicated to COVID-19 patients, and an official of the Department of Natural Resources and Environment of An Giang Province and staff of the Urban Infrastructure Construction Investment Projects Management Unit (under the People's Committee of Ho Chi Minh City) for sharing their insights on the provincial administration of COVID-19 waste. Additional thanks go to the researchers of the Department of Administration and Planning–Institute for Environment and Resources at the Vietnam National University-Ho Chi Minh City (VNU-HCM) for their input on the challenges associated with securing correct management of COVID-19 waste in the absence of social restrictions and on the national strategies of waste management during the pandemic.

Data availability The data that support the findings of this study are available from the corresponding author, Trang DT Nguyen, upon reasonable request.

References

1. WHO (2022) Strategic preparedness, readiness and response plan to end the global COVID-19 emergency in 2022. https://www.who.int/publications/m/item/strategic-preparedness-readiness-and-response-plan-to-end-the-global-covid-19-emergency-in-2022. Accessed 3 Apr 2022
2. WHO (2022) Enhancing response to Omicron SARS-CoV-2 variant: technical brief and priority actions for member states—updated #6: 21 January 2022. https://www.who.int/publications/m/item/enhancing-readiness-for-omicron-(b.1.1.529)-technical-brief-and-priority-actions-for-member-states. Accessed 27 Apr 2022
3. WHO Regional Office for Europe (2022) Statement—two years on, we could be entering a new phase in the pandemic with plausible hope for stabilization, yet too early to drop our guard. https://www.euro.who.int/en/media-centre/sections/statements/2022/statement-two-years-on,-we-could-be-entering-a-new-phase-in-the-pandemic-with-plausible-hope-for-stabilization,-yet-too-early-to-drop-our-guard. Accessed 28 Apr 2022
4. ADB (2022) Southeast Asia rising from the pandemic. Asian Development Bank, Manila, Philippines. https://www.adb.org/publications/southeast-asia-rising-from-pandemic. Accessed 9 May 2022
5. NSC (2022) Two-year results of COVID-19 pandemic prevention and control. Hanoi. https://moh.gov.vn/documents/174521/1197117/4.+BC+k%E1%BA%BFt+qu%E1%BA%A3+02+n%C4%83m+tri%E1%BB%83n+khai+c%C3%B4ng+t%C3%A1c+ph%C3%B2ng%2C+ch%E1%BB%91ng+d%E1%BB%8Bch+COVID-19.pdf/e3254b2a-c902-4696-b0c7-cc4427b8f992. Accessed 20 Jan 2022
6. WHO (2022) Global analysis of healthcare waste in the context of COVID-19: status, impacts and recommendations. World Health Organization, Geneva. https://apps.who.int/iris/bitstream/handle/10665/351189/9789240039612-eng.pdf?sequence=1&isAllowed=y. Accessed 2 Feb 2022
7. UNEP (2022) Guidance on policy and legislation for integrated waste management during a pandemic. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/39705/policy_legislation.pdf?sequence=3&isAllowed=y. Accessed 27 Apr 2022
8. IFC-World Bank (2020) COVID-19's impact on the waste sector. https://www.ifc.org/wps/wcm/connect/dfbceda0-847d-4c16-9772-15c6afdc8d85/202006-COVID-19-impact-on-waste-sector.pdf?MOD=AJPERES&CVID=na-eKpI. Accessed 6 Mar 2022
9. UNEP (2020) COVID-19 Waste management Factsheets. http://www.unenvironment.org/resources/factsheet/covid-19-waste-management-factsheets. Accessed 8 Sep 2020
10. UNEP (2020) Waste management during the COVID-19 pandemic from response to recovery. https://wedocs.unep.org/bitstream/handle/20.500.11822/33416/WMC-19.pdf?sequence=1&isAllowed=y. Accessed 24 Aug 2020
11. UN Habitat (2020) Strategy guidance: solid waste management response to COVID-19. https://unhabitat.org/sites/default/files/2020/05/un-habitat_strategy_guidance_swm_reponse_to_covid19.pdf. Accessed 4 May 2021

12. WHO, UNICEF (2020) Water, sanitation, hygiene, and waste management for the COVID-19 virus – Interim guidance: 19 March 2020. https://apps.who.int/iris/bitstream/handle/10665/331499/WHO-2019-nCoV-IPC_WASH-2020.2-eng.pdf?sequence=1&isAllowed=y. Accessed 10 Aug 2020
13. ADB (2020) Managing infectious medical waste during the COVID-19 pandemic. https://www.adb.org/sites/default/files/publication/578771/managing-medical-waste-covid19.pdf. Accessed 19 Dec 2020
14. UNDP (2020) Rapid assessment on the health care waste management in the context of COVID-19. https://api.savinglivesustainably.org/documents/file/fcdd3e31cc0fbff265fac9a4ff51d096/full/hash. Accessed 8 Feb 2022
15. Almulhim AI, Ahmad I, Sarkar S, Chavali M (2021) Consequences of COVID-19 pandemic on solid waste management: scenarios pertaining to developing countries. Remediation (N Y). https://doi.org/10.1002/rem.21692.10.1002/rem.21692
16. Hantoko D, Li X, Pariatamby A et al (2021) Challenges and practices on waste management and disposal during COVID-19 pandemic. J Environ Manag 286:112140. https://doi.org/10.1016/j.jenvman.2021.112140
17. Barua U, Hossain D (2021) A review of the medical waste management system at Covid-19 situation in Bangladesh. J Mater Cycles Waste Manag 23:2087–2100. https://doi.org/10.1007/s10163-021-01291-8
18. Ouhsine O, Ouigmane A, Layati E et al (2020) Impact of COVID-19 on the qualitative and quantitative aspect of household solid waste. Global J Environ Sci Manag 6:41–52. https://doi.org/10.22034/GJESM.2019.06.SI.05
19. Oyedotun TDT, Kasim OF, Famewo A et al (2020) Municipal waste management in the era of COVID-19: perceptions, practices, and potentials for research in developing countries. Res Glob 2:100033. https://doi.org/10.1016/j.resglo.2020.100033
20. Requena-Sanchez N, Carbonel-Ramos D, Campodónico LFD (2022) A novel methodology for household waste characterization during the COVID-19 pandemic: case study results. J Mater Cycles Waste Manag 24:200–209. https://doi.org/10.1007/s10163-021-01309-1
21. Salvaraji L, Jeffree MS, Avoi R et al (2020) Exposure risk assessment of the municipal waste collection activities during COVID-19 pandemic. J Public Health Res. https://doi.org/10.4081/jphr.2020.1994
22. World Bank (2021) The impact of COVID-19 on plastic waste management in South Asia: challenges and policy recommendations. World Bank
23. Tripathi A, Tyagi VK, Vivekanand V et al (2020) Challenges, opportunities and progress in solid waste management during COVID-19 pandemic. Case Stud Chemi Environ Eng 2:100060. https://doi.org/10.1016/j.cscee.2020.100060
24. Zand AD, Heir AV (2021) Environmental impacts of new Coronavirus outbreak in Iran with an emphasis on waste management sector. J Mater Cycles Waste Manag 23:240–247. https://doi.org/10.1007/s10163-020-01123-1
25. El-Ramady H, Brevik EC, Elbasiouny H et al (2021) Planning for disposal of COVID-19 pandemic wastes in developing countries: a review of current challenges. Environ Monit Assess 193:592. https://doi.org/10.1007/s10661-021-09350-1
26. Sharma HB, Vanapalli KR, Cheela VS et al (2020) Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resour Conserv Recycl 162:105052. https://doi.org/10.1016/j.resconrec.2020.105052
27. Adelodun B, Ajibade FO, Ibrahim RG et al (2021) Insights into hazardous solid waste generation during COVID-19 pandemic and sustainable management approaches for developing countries. J Mater Cycles Waste Manag. https://doi.org/10.1007/s10163-021-01281-w
28. Shams M, Alam I, Mahbub MS (2021) Plastic pollution during COVID-19: plastic waste directives and its long-term impact on the environment. Environ Adv 5:100119. https://doi.org/10.1016/j.envadv.2021.100119
29. Uddin MA, Afroj S, Hasan T et al (2022) Environmental Impacts of personal protective clothing used to combat COVID-19. Adv Sustain Syst 6:2100176. https://doi.org/10.1002/adsu.202100176
30. UN (2020) Impact of the COVID-19 pandemic on trade and development–transitioning to a new normal. Geneva. https://unctad.org/system/files/official-document/osg2020d1_en.pdf. Accessed 9 May 2022
31. UN-Habitat (2021) Cities and pandemics: towards a more just, green and healthy future. https://unhabitat.org/sites/default/files/2021/03/cities_and_pandemics-towards_a_more_just_green_and_healthy_future_un-habitat_2021.pdf. Accessed 9 May 2022
32. Gautam P, Salunke D, Lokandwala S (2022) Chapter 15—environmental policies and strategies for COVID-19. In: Rawtani D, Hussain CM, Khatri N (eds) COVID-19 in the environment. Elsevier, pp 297–308
33. Mahyari KF, Sun Q, Klemeš JJ et al (2022) To what extent do waste management strategies need adaptation to post-COVID-19? Sci Total Environ 837:155829. https://doi.org/10.1016/j.scitotenv.2022.155829
34. Ranjbari M, Shams Esfandabadi Z, Shevchenko T et al (2022) Mapping healthcare waste management research: past evolution, current challenges, and future perspectives towards a circular economy transition. J Hazard Mater 422:126724. https://doi.org/10.1016/j.jhazmat.2021.126724
35. Sharma HB, Vanapalli KR, Samal B et al (2021) Circular economy approach in solid waste management system to achieve UN-SDGs: solutions for post-COVID recovery. Sci Total Environ 800:149605. https://doi.org/10.1016/j.scitotenv.2021.149605
36. Teymourian T, Teymoorian T, Kowsari E, Ramakrishna S (2021) Challenges, strategies, and recommendations for the huge surge in plastic and medical waste during the global COVID-19 pandemic with circular economy approach. Mater Circ Econ 3:6. https://doi.org/10.1007/s42824-021-00020-8
37. Gupta G (2022) Chapter 14—management of COVID-19 waste. In: Rawtani D, Hussain CM, Khatri N (eds) COVID-19 in the environment. Elsevier, pp 277–294
38. Hasija V, Patial S, Kumar A et al (2022) Environmental impact of COVID-19 Vaccine waste: a perspective on potential role of natural and biodegradable materials. J Environ Chem Eng 10:107894. https://doi.org/10.1016/j.jece.2022.107894
39. Marfe G, Perna S, Hermann A (2022) Challenges in healthcare waste management of the UN 2030 agenda in the COVID-19 era. Am J Environ Sci 18:20–41. https://doi.org/10.3844/ajessp.2022.20.41
40. Purnomo CW, Kurniawan W, Aziz M (2021) Technological review on thermochemical conversion of COVID-19-related medical wastes. Resour Conserv Recycl 167:105429. https://doi.org/10.1016/j.resconrec.2021.105429
41. WHO Vietnam-MOH (2021) Vietnam COVID-19 situation report #64- Epidemiological report as of 17 October 2021, 18:00. https://www.who.int/docs/default-source/wpro---documents/countries/viet-nam/covid-19/viet-nam-moh-who-covid-19-sitrep_17oct2021.pdf?sfvrsn=60099685_5. Accessed 27 Apr 2022
42. MOH (2022) National report on medical care activities in 2021 and solutions for 2022. Hanoi. https://adminmoh.moh.gov.vn/documents/20182/0/3.+B%C3%A1o+c%C3%A1o+ng%C3%A0nh+Y+t%E1%BA%BF+2021.pdf/3ae93a62-4e42-4d57-86b7-e9e7c0787b39. Accessed 20 Jan 2022

43. Nguyen DT, Kawai K, Nakakubo T (2021) Estimation of COVID-19 waste generation and composition in Vietnam for pandemic management. Waste Manag Res 39:1356–1364. https://doi.org/10.1177/0734242X211052849
44. World Bank (2019) Vietnam hospital waste management support project. http://documents1.worldbank.org/curated/fr/364951583249035788/pdf/Vietnam-Hospital-Waste-Management-Support-Project.pdf. Accessed 29 Oct 2020
45. MONRE (2011) National Environment Report 2011. Hanoi. http://vea.gov.vn/Documents/bao%20cao%20moi%20truong%20quoc%20gia/BCMTQG2011_BTNMT.pdf. Accessed 7 Oct 2019
46. MONRE (2017) National Environment Report 2017. Hanoi. http://vea.gov.vn/Documents/bao%20cao%20moi%20truong%20quoc%20gia/bao%20cao%20moi%20truong%202017-danen.pdf?csf=1&e=GcRbRt%20. Accessed 7 Oct 2019
47. MOH (2022) Re-examination of treatment COVID-19 related waste for pandemic prevention and control. https://moh.gov.vn/tin-noi-bat/-/asset_publisher/3Yst7YhbkA5j/content/ra-soat-anh-gia-xu-ly-chat-thai-y-te-trong-phong-chong-dich-covid-19. Accessed 26 Apr 2022
48. Nguyen TDT, Kawai K, Nakakubo T (2022) Capacity assessment to secure COVID-19 waste treatment in Vietnam. J Mater Cycles Waste Manag. https://doi.org/10.1007/s10163-022-01529-z
49. Le HT, Quoc KL, Nguyen TA et al (2022) Medical-waste chain: a medical waste collection, classification and treatment management by blockchain technology. Computers 11:113. https://doi.org/10.3390/computers11070113
50. UNEP-IETC (2012) Compendium of technologies for treatment, destruction of healthcare waste. https://wedocs.unep.org/bitstream/handle/20.500.11822/8628/IETC_Compendium_Technologies_Treatment_Destruction_Healthcare_Waste.pdf?sequence=3&isAllowed=y. Accessed 30 Mar 2021
51. World Bank (2018) Solid and industrial hazardous waste management assessment: Options and action area to implement the national strategy. Hong Duc Publishing House. https://documents1.worldbank.org/curated/en/352371563196189492/pdf/Solid-and-industrial-hazardous-waste-management-assessment-options-and-actions-areas.pdf. Accessed 9 Oct 2019
52. CEID-VEA (2020) Upward trend of generation observed in municipal and hazardous waste. http://ceid.gov.vn/luong-chat-thai-ran-va-chat-thai-nguy-hai-phat-sinh-ngay-cang-lon/. Accessed 12 Mar 2021
53. WHO Vietnam-MOH (2022) Vietnam COVID-19 situation report #85- Epidemiological report as of 20 March 2022, 18:00. https://www.who.int/docs/default-source/wpro---documents/countries/viet-nam/covid-19/viet-nam-moh-who-covid-19-sitrep-85_20mar2022.pdf?sfvrsn=1d681357_7&download=true. Accessed 27 Apr 2022
54. MONRE (2020) National Environment Report 2019. Hanoi. http://www.monre.gov.vn/Portal/Documents/2020/11/Ban%20Giay%20phep%20in_Bao%20cao%20hien%20trang%20moi%20truong%20%281%29.pdf. Accessed 15 Apr 2020
55. DONRE HCMC (2021) Report on environment and natural resources governance in Ho Chi Minh City in 2021 and solutions for 2022. HCMC. http://www.donre.hochiminhcity.gov.vn/thong-tin-hoat-dong/default.aspx?Source=%2fthong-tin-hoat-dong&Category=Ca%cc%81c+c%c3%b4ng+ta%cc%81c+kha%cc%81c&ItemID=4638&Mode=1. Accessed 28 Dec 2021
56. VIHEMA-MOH (2017) Management of medical waste at ward-level medical clinics. https://vihema.gov.vn/thuc-trang-cong-tac-quan-ly-chat-thai-ran-y-te-tai-cac-tram-y-te-xa-o-viet-nam.html. Accessed 16 Mar 2021
57. WHO, UNICEF (2020) Water, sanitation, hygiene and waste management for SARS-CoV-2, the virus that causes COVID-19—Interim guidance: 29 July 2020. https://www.who.int/publications/i/item/WHO-2019-nCoV-IPC-WASH-2020.4. Accessed 25 May 2022
58. WHO (2020) Rational use of personal protective equipment for COVID-19 and considerations during severe shortages: Interim guidance, 23 December 2020. https://apps.who.int/iris/rest/bitstreams/1323807/retrieve. Accessed 1 Nov 2021