Waste Management 141 (2022) 271–281

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Safety at waste and recycling industry: Detection and mitigation of waste fire accidents

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ARTICLE INFO

Keywords:
Waste fire
Waste management
Waste emissions
Waste industry
Fire hazard
Safe storage

ABSTRACT

In this study, NASA's VIIRS (Visible Infrared Imaging Radiometer Suite) fire hotspots and data of the Swedish Civil Contingencies Agency (MSB), collected between 2012 and 2018, was integrated to characterize waste fire incidents that were detected by VIIRS and reported to MSB (DaR), detected by VIIRS but not reported to MSB (DbNR) and that are reported to MSB but not detected by VIIRS (RbND). Results show that the average number of open waste fire incidents per million capita per year (AFIPMC) in Sweden, for the period 2012–2018, ranges from 2.4 to 4.7. Although a weak correlation exists ($r = 0.44$, $P = 0.1563$, one tailed) between years and number of fire incidents (MSB + VIIRS fires), a continuous increase in number of fire incidents was recorded between 2014 and 2018. It is concluded that the use of satellite data of fire anomalies, in-combination with the use of incident reports, will help in formalizing more reliable and comprehensive waste fire statistics. Another focus area of the article is to consolidate the recommendations and routines for safe storage of waste and biofuels and to present the lessons that can be learnt from past fire incidents. The article also discusses the technical, political, economic, social, and practical aspects of waste fires and provide a baseline for future research and experimentation.

1. Introduction

Waste fires are common at all stages of the waste recycling chain and concern all businesses that are involved in collection, sorting, pre-assessment, recycling, energy recovery and transportation of waste (Nigl et al. 2020; Ibrahim, 2020a). The issue of fires in the waste and recycling industry, which is referred as an epidemic by Fogelman, (2018), can have serious socio-economic, environmental, and occupational health and safety consequences. The hazard of waste fires, due to increased frequency and severity, is a growing concern for many countries around the globe, such as the United Kingdom, Sweden, Austria, Germany (Nigl et al. 2020), USA (Fogelman, 2018), Italy (Mazzucco et al. 2020) and Thailand (Wiwanitkit, 2016). The repercussions of waste fires are local, regional as well as global in nature, and have both short- and long-term consequences. Even the regional-scale impacts of waste fires, when combined and weighted together, have created a challenge, which is global in nature (see Fig. 1).

Emissions from waste fires are persistent, bio-accumulative, and toxic in nature, and contaminate air (Lemieux et al. 2004), soil, ground water, surface water (Cocean et al. 2020) and can e.g. lead to fish mortality (Barber et al. 2003). Due to its highly toxic nature, waste fire emissions often give rise to mass scale environmental and health related emergencies for downwind residing population (Mazzucco et al. 2020; Wiwanitkit, 2016). Studies provided evidence that emissions from waste fires pose chronic health hazards, such as lung cancer (Wiwanitkit, 2016), pregnancy disorders (Mazzucco et al. 2019) and pulmonary cardiovascular and neurological ailments (Adetona et al. 2020). Currently, waste fires are the most dominate source of emissions of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) in Europe and threatening the public health in the whole European region (Rada et al. 2018). According to the recent estimates from the Global Burden of Disease study, smoke from open combustion of municipal solid waste (MSW) causes 270,000 premature adult deaths annually (Adetona et al. 2020).

Most of waste storage sites are located at urban fringe and fire incident at these sites pose serious hazard for the ignition of both urban fires and wildfires (Ibrahim, 2020a). Incidents of ignition of wildfires caused by waste fires are becoming more common in Sweden and regularly get coverage in the electronic and print media (Expressen, 2018a; Expressen, 2018b; Expressen, 2019; Razooq et al., 2020), and several such incidents are reported to The Swedish Civil Contingencies Agency (MSB) (Ekberg, 2020). The wildfires can develop from waste

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https://doi.org/10.1016/j.wasman.2022.02.004
Received 23 September 2021; Received in revised form 5 December 2021; Accepted 3 February 2022
Available online 11 February 2022

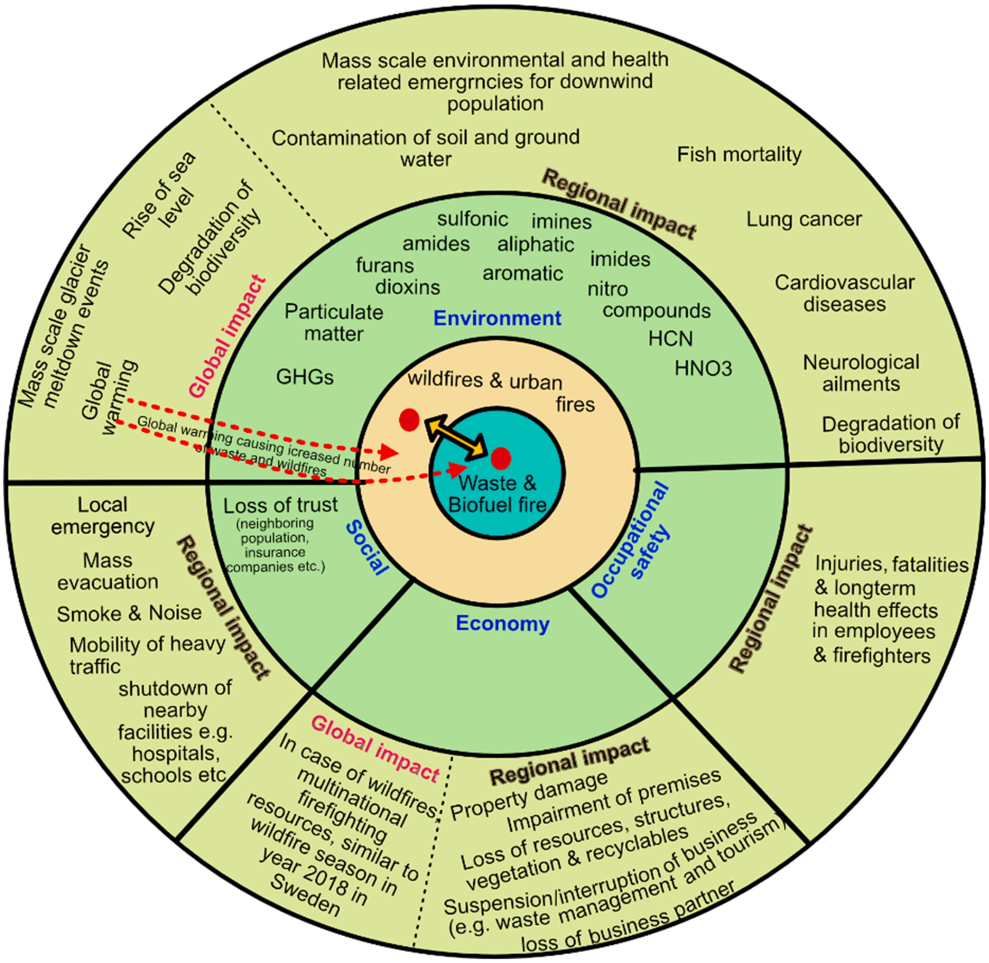

Fig. 1. Venn diagram showing regional and global repercussions of waste fires.

fires either by direct flame contact, through radiation exposure or by firebrands (Ibrahim, 2020a) and the latter factor i.e., firebrands, in general, is known to ignite multiple spot fires up to 2.4 km away from the primary fire (Aronson, 2012). Black carbon released from the biomass fires in the Arctic Circle (Sweden in particular) is primarily responsible for darkening (Berwyn, 2018a) and largescale melting of Greenland ice sheet (Keegan et al., 2014; Berwyn, 2018b; NSIDC, 2019), and affecting climate on regional and even on global scale by scattering or absorbing radiation and changing cloud properties (NOAA, 2020).

Waste fire incidents are progressively becoming one of the important precursors of wildfires, but in the past, accounting of socio-economic and environmental damages of both is performed in isolation from each other, without considering their compound effect (Ibrahim et al. 2013; Persson et al. 2014). Similarly, indirect costs of waste fires (e.g., emission externalities, nuisance and chronic health effects on nearby population, closure of nearby businesses, hospitals, and schools etc.) are rarely considered in past studies. An estimate made, based on year 2011–12, shows that the direct annual cost of waste and biofuel fires in Sweden is about 150–350 million SEK (Persson et al. 2014), which is just the tip of the iceberg, as many incidents in the waste recycling industry are handled by its own personnel without help from the fire and rescue service (and therefore not included in the MSB database[1]) or left unreported due to poor and inconsistent data compilation routines (Persson et al. 2014; McIntyre, 2018). Even some well-known biomass fire incidents were found missing during targeted searches made in the data bank of MSB (Persson et al. 2014). The main reason is that the content is very much dependent on how the fire information is interpreted and registered into the database, and therefore maybe not found in a specific search, although some incidents seem to be completely missing in the database. Furthermore, the current available data on waste fire incidents lacks granularity (the size in which data fields are sub-divided) and is a limiting factor for developing mitigation strategies and policy guidelines. The Swedish Environmental Protection Agency has stressed the need for improving the quality of waste related statistics as it is a prerequisite for being able to choose the most appropriate measures for a circular economy (Naturvårdsverket, 2020). In this view, there is a need to understand the limitations of incident reporting routines that are currently practiced by fire and rescue services and MSB, and how it could be improved. Therefore, one objective of the article is to analyse the risk of waste fires in Sweden based on two different data sources: (a). *statistical data bank of MSB* and (b). *NASA's satellite data of VIIRS (Visible Infrared Imaging Radiometer Suite) fire anomalies*, and to present the limitations associated with these data sources for compilation of waste fire statistics.

A second important aspect related to hazard of waste fires is that it is often seen through the lens of demographic attributes alone. Nigl et al. (2020) shows that waste fire incidents are spatially correlated with the distribution patterns of the population. This macroscopic approach though identifies the risk in spatial dimension but barely provide any opportunity to respond to the actual risk. In contrast to this, there is a need for investigating the different attributes of storage sites, such as

[1] MSB compiles national data of fire incidents based on the incidents' report submitted by rescue service agency and does not include the incidents in which fire rescue agencies are not mobilized.

storage routines, storage techniques and design characteristics, which can provide a better opportunity to reduce both likelihood and consequences of waste fires by directly addressing the problem. In this view, various design related aspects of waste storage sites are discussed, and recommendations have been derived based on experience gathered, both nationally in Sweden (Lönnermark et al., 2018; Lönnermark et al. 2019) and internationally (ISO, 2021).

2. Methodology

NASA offers multiple real time products of varying resolution for tracking land based thermal anomalies/hotspots e.g., MODIS (resolution 1000 m) and VIIRS (resolution 375 m). In this study, VIIRS fire anomalies, which has highest resolution among the available data products was employed for analysis. VIIRS fire hotspots (GIS shape file, comprised of 9909 vector points[2] in WGS84 coordinate system) recorded by NASA's Suomi-National-Polar-orbiting-Partnership (S-NPP) satellite (NASA, 2019) in Sweden during 2012–2018 are imported in ArcGIS as a feature-layer (see Fig. 2b). Using satellite imagery as a base map in ArcGIS[3] (see base map in Fig. 3) and VISS[4] waste handling sites' data base (see Fig. 2c), VIIRS fire hotspots were categorised in two categories, waste fires (see Fig. 2d) and other fires (i.e., forest fire, grass fire, agricultural fire, build-up area fire, and other industrial fires). Another feature layer (WGS84 coordinate), comprising of 163 waste fire incidents[5] that are reported to MSB during 2012–2018, under the category "*Garbage disposal, recycling, sewage or treatment plants*" was created (see Fig. 2e). An overlay analysis of these two feature layers was performed in ArcGIS (i.e., *first,* starting from MSB waste fires and looking for VIIRS fire anomalies and vice versa, and three sub-classes of waste fires were identified: (a). detected by VIIRS and reported to MSB (DaR); (b). detected by VIIRS but not reported to MSB (DbNR) and (c). reported to MSB but not detected by VIIRS (RbND) (see Fig. 2). These sites involve activities like, waste collection, sorting, pre-treatment, recycling, and landfilling.

The VIIRS fire hotspot data has a spatial resolution of 375 m, which means, a certain waste fire incident is marked, either by single VIIRS fire hotspot (in case, fire's foot-print area less than 375×375 m^2) or by multiple hotspots (in case, fire's foot-print area $> 375 \times 375$ m^2). Fig. 3 is an example of a waste fire incident that spanned over two days and is marked by 11 VIIRS fire anomalies. The date, time, and geographical positioning of VIIRS fire anomalies (The shape file of VIIRS hotspots that was taken from NASA carries both temporal and spatial details of the hotspots) give possibility for each waste fire incident detected by VIIRS to be compared in time and space with those that are registered with MSB. In this study, all the VIIRS fire anomalies detected on consecutive days at any site are considered as one fire incident as it can take more than one day to extinguish a waste fire.

The annual number of waste fire incidents per million capita (FIPMC) and its average value (AFPMC) are important parameters for studying waste fire hazards (Nigl et al. 2020) and calculated using Eq.1 and Eq.2.

$$FIPMC_i = \frac{N_i}{P_i} \times 10^6 \quad (1)$$

$$AFIPMC = \frac{\sum_{i=1ton}\left(\frac{N_i}{P_i} \times 10^6\right)}{n} \quad (2)$$

Where, "N" stands for number of waste fire incidents, "P" is the Swedish population in a certain year[6], "i" corresponds to ith year and "n" is total number of years over which average is to be calculated.

3. Results and discussion

3.1. Frequency and causes of waste fires

The value of FIPMC is increasing in Sweden, and in other parts of the world (Nigl et al. 2020). The average number of open waste fire incidents per million capita per year (AFIPMC) in Sweden for the period 2012–2018 ranges from 2.4 (based on MSB (DaR + RbND) fire incidents) to 4.7 (MSB + VIIRS fires (DbNR)) (see Table 1 and Fig. 4). Although a weak correlation exists ($r = 0.44$, $P = 0.1563$, one tailed) between years and number of fire incidents (MSB + VIIRS fires), a continuous increase in number of fire incidents was recorded between 2014 and 2018. The results in this study are in close agreement with the estimates made by Mikaelson et al. (2021), which pointed out that approximately 60 to 70 waste fires occur in Sweden every year.

Analysis of MSB fire statistics shows that no specific cause is assigned to about half of the waste fire incidents (≈ 46%), and human factors, such as arson, sparks, equipment failure, hot work, other fires, fireworks, grilling, and children playing with fires, altogether contributes to ≈ 23% of waste fire incidents. The single most *known-cause* (≈ 21%) of the waste fire incidents is "*self-ignition*". According to EU regulation No. 286/2011[7], self-ignition is defined as "*a process where the gradual reaction of that substance or mixture with oxygen (in the air) generates heat. If the rate of heat production exceeds the rate of heat loss, then the temperature of the substance or mixture will rise which, after an induction time, may lead to self-ignition and combustion*", however, in recent years, battery-fires are also started to be referred as "self-ignition" fires (Si et al. 2018). It is also observed that fire incidents for which actual root cause is not obvious are often reported as "*self-ignition*" (Nigl et al. 2020). Statistics shows that the underlying causes of large fractions of waste fires is still not known. More research is required to understand battery-contamination in household and industrial waste fractions, and to know during which processing stage and under what conditions battery fires are common.

3.2. Ambiguities related to waste fire statistics

3.2.1. Cause-category

It is observed in the MSB data bank that for some waste fire incidents, *cause-category* is not assigned correctly. For example, the cause of a waste fire at a site (56.744688 14.488874) on 2018–06-01 is stated as "*Återantändning av brand från tidigare räddningsinsats (In English: Re-ignition of fire from previous rescue operation)*" but the initial incident of waste fire is missing in the data bank. This shows either "*cause-category*" of above-mentioned incident is registered incorrectly, or the initial event of waste fire incident was not reported to MSB.

There is need to develop standardized definition of each "*cause-category*", and for better record keeping and understanding the risk of waste fire incidents, additional "*sub-cause-categories*" should be introduced. For example, *overheated conveyor belt,* is not considered as a separate "*cause-category*" today, even though it is a common cause of waste fires at sites that involve staged operations, such as sorting, comminution and baling etc. and known to have resulted in complete

[2] There are 9909 land based VIIRS fire anomalies (excluding volcanoes/glint surfaces e.g., offshore, water bodies or roads) detected in Sweden during 2012–18 (NASA, 2020).

[3] The base map in ArcGIS is the intellectual property of Esri and is used herein under license.

[4] Water-Information-System-of-Sweden (VISS), https://viss.lansstyrelsen.se/About.aspx.

[5] Geographical coordinates of only 163 of 393 waste fire incidents are available in the records of MSB.

[6] Taken from the official register of the Statistical Bureau of Sweden (www.scb.se)

[7] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:083:0001:0053:EN:PDF

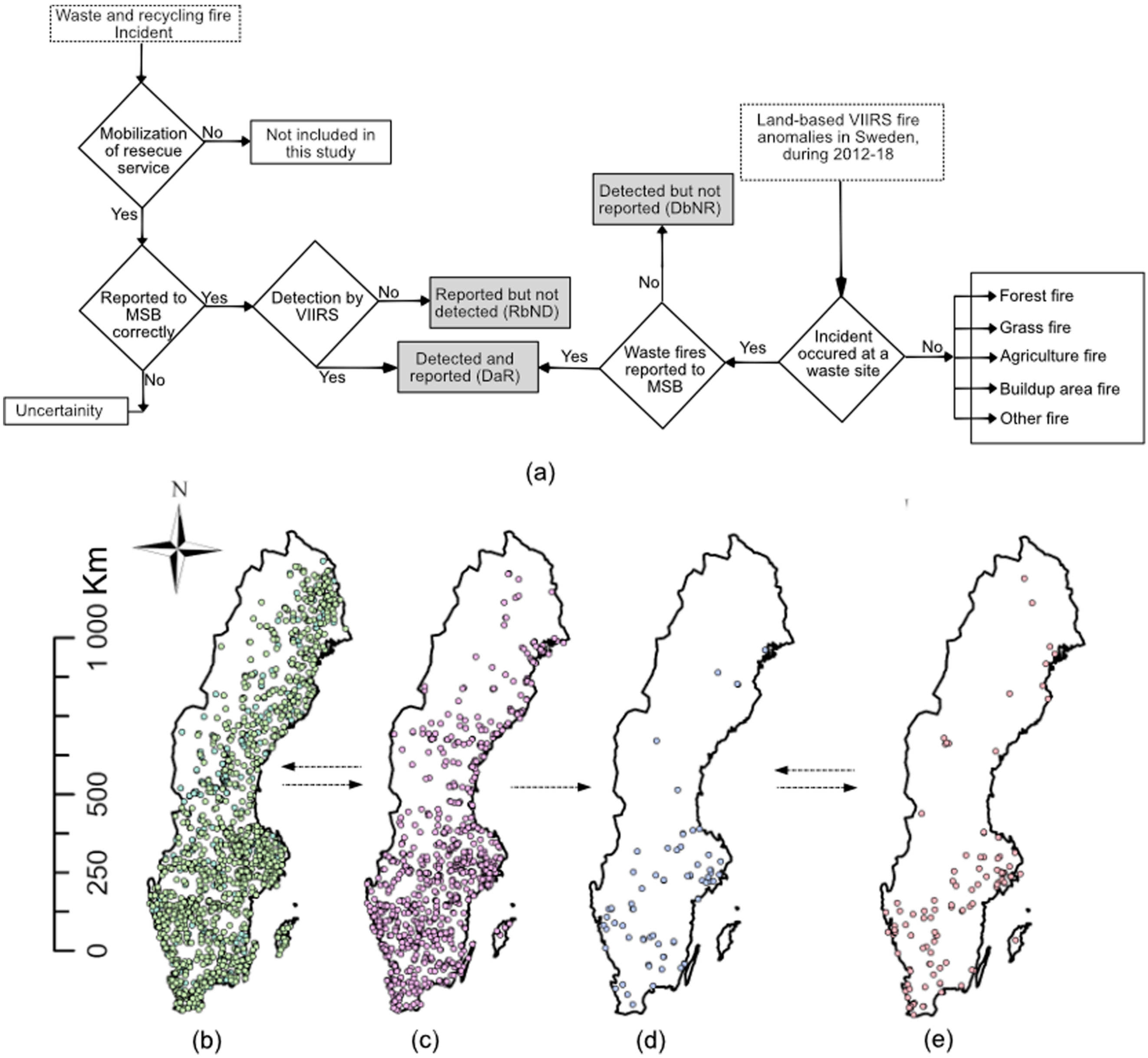

Fig. 2. The framework of the study: (a). block diagram; (b). VIIRS fire anomalies 2012–2018; (c). VISS waste sites dataset; (d). VIIRS waste fire anomalies; (e). MSB waste fires.

destruction of entire recycling facilities on several occasions (IFW, 2020; Sharman, 2016). On the other hand, too much detailed reporting systems can also give rise to uncertainties, therefore, there is a need to make the reporting system intuitive and easy to fill out in a good and systematic way.

3.2.2. Activity or situation

In the MSB data base, waste fires are sub-classified based on activity/situation e.g., *residential settings*, *waste disposal and recycling, industrial setting with energy production, other industries,* etc. In several instances, inconsistent "*activity/situation*" was assigned to waste sites by fire and rescue services. For example, GIS analysis in ArcGIS shows that for 12 fire incidents that are reported at waste site (60.638494 16.877571) between 2012 and 2018, the "activity/situation" of the waste site for 7 incidents is stated as "*Verksamhet inte knuten till en byggnad, (In English: Business-not-linked-to-building)*", for 4 incidents is "*Sophantering, återvinning, avlopps- eller reningsverk (In English: Garbage disposal, recycling, sewage or treatment plants)*" and for 1 incident is "*Kraft- eller värmeverk (In English: Power or heating plant)* "[8]. It is suggested to develop consistent and self-explanatory terminologies for defining activity classes, to improve the incident reporting by fire and rescue services and interpretations made by MSB, during data compilation.

3.2.3. Coordinates and compilation of waste fire statistics

The overlay analysis shows that the coordinates of 50 of 163 MSB waste fires, instead of laying above waste sites are located e.g., above build-up areas or agricultural lands. The chief causes of discrepancies in coordinates are attributed to poor incident reporting routines by fire rescue service agencies and potential errors during conversion of coordinates from one coordinate system to the other (McIntyre, 2018; Ekberg, 2020). Commonly, fire and rescue services register the

[8] According to MSB the category "*Business not linked to building*" includes roads, bridges, parking spaces, parks, fields, forests, water etc., and waste storage and treatment is referred to the category "*Garbage disposal, recycling, sewage or treatment plants*" (Ekberg, 2020).

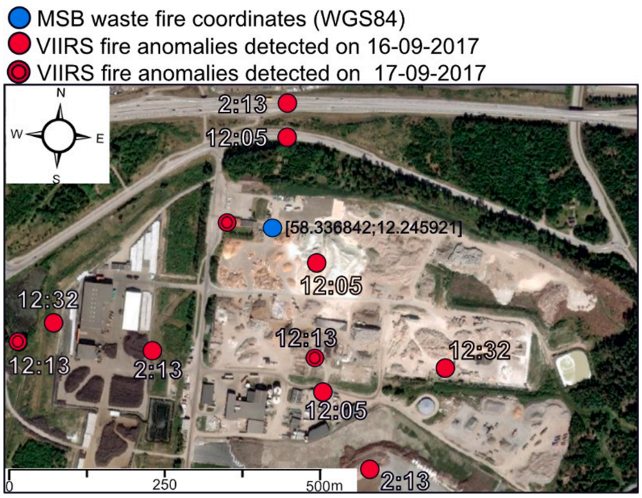

Fig. 3. The details of VIIRS fire anomalies (WGS84 coordinates, date, and time of acquisition of fire anomalies) and MSB waste fire (WGS84 coordinates) [base map source: ESRI (ArcGIS Pro 2.5.0)].

coordinates of SOS signal as the coordinates of the incident, but in many cases coordinates of SOS signal can be different from that of waste site (McIntyre, 2018). The overlay analysis shows that discrepancies associated with coordinates of waste sites has gradually reduced over the years, however, there are still a distinct number of waste fires that are detected but not reported (DbNR) and that are reported but not detected (RbND) (see Fig. 4a). There are only 11 of 163 (≈ 7 %) MSB waste fire incidents that were detected by VIIRS and also reported to MSB (DaR). This suggests that the actual number of waste fires are much larger than the total number of incidents reported to MSB. This stresses the need to employ a complementary approach i.e., along with improving the incident reporting routines of fire rescue agencies, VIIRS fire anomaly data can also be used for registering the waste fire incidents.

From 2020, MSB has started to use NASA's VIIRS fire anomalies satellite data for the detection of "*wildfires*", and feasibility to use European Sentinel-2 satellite data is underway in another project (Skogforsk, 2020). In this view, it is suggested that the use of VIIRS fire anomalies as a supplementary method shall give MSB a possibility for counter verification of reported incidents and to register even those waste fires that are handled by the facility operators themselves, without involving fire and rescue services, therefore, can help in formalizing more reliable waste fire statistics. Resultantly, governmental authorities shall have access to more credible fire statistics and would be able to optimally allocate the resources and to develop policies. Another advantage of using satellite data as a complementary approach is to register the duration of waste fire incidents more accurately. In the current study, two waste fire incidents in 2018 and one incident in 2019, lasted for two days, and one incident in 2016, lasted for 3 days.

More research is still required for understanding the potential sources of errors and limitations of current quality flags associated with the use of VIIRS fire anomalies for the detection of waste fires. In general, reflection from glint surfaces (e.g., roads, water bodies, glass roofs etc.), can cause overestimate of fire incidents, and limitation of infrared light to pass through clouds[9] and low scanning frequency of satellites (e.g., Sentinel-2 provides images of a site after every two or three days), can cause underestimation of fire incidents (Ibrahim, 2020a; San-Miguel-Ayanz et al., 2012; Skogforsk, 2020). The *cold sky reflection* is another potential source of error that is introduced when satellite pictures are taken during sunrise (Abramowicz and Chybiorz, 2019). The degree of error associated with VIIRS fire anomalies can vary for day and night-time pixels and is even site specific. For example, day-time commission error rate for urban false alarm is estimated to be 0.03% at global level but for eastern China is nearly 40% (Schroeder et al. 2014). Moreover, for the region having South Atlantic Magnetic Anomaly (110°W <> 11°E and 7°N <> 55°S), VIIRS fire anomalies can have artificial high brightness temperature and cannot be readily identified nor excluded using the available quality flags employed in the VIIRS fire detection algorithm (Schroeder et al. 2014). In future, to improve the confidence on waste fire statistics, there is need to perform calibration studies to determine the degree of errors, specifically associated with the detection of waste fires.

3.3. Current practices and mitigation of waste fires

3.3.1. Safe separation distance

A very basic safety question related to waste and biofuel storage is *"how much two piles should be separated to prevent spread of fire from one unit to the other?"*. Currently, there are no comprehensive performance-based guidelines for large-scale storage of fuels. However, there are some recommendations (e.g., CFPA, 2014; Lönnermark et al., 2019; WISH, 2020) available that are based on best operating practices, firefighter experiences and a limited number of experiments. The Confederation of Fire Protection Associations in Europe, recommended to have maximum footprint area of 400 m^2 and with a maximum height of 5 m (CFPA, 2014). The waste industry safety health forum (WISH) of the UK has proposed separation distances of 5 m, 10.5 m and 12 m for loose stockpiles of ordinary waste with footprint area of 5×5 m^2, 25×25 m^2 and 50×50 m^2, respectively, however, these recommendations are valid only for 4 m high piles, without considering effect of wind and hazards of firebrands (WISH, 2020). Moreover, the values of these recommended separation distances are based on the amount of heat emitted per unit of area (i.e., heat flux density) of a burn-face (WISH, 2020). It seems that by referring only to the burn-face, without considering flame height, the contribution of radiative heat flux from the flames is neglected by WISH, which can be significant in this type of fires. There is also a debate regarding the use of heat flux versus ignition temperature as a criterion for studying fire propagation (Nyzhnyk et al. 2019).

Because of the limited number of detailed experimental studies, there are limited number of detailed recommendations of safe separation distance (SSD) that could provide required safety against spread of fire at waste storage sites and for other similar situations. For example, in view of informal settlement dwellings, Cicione et al. (2019) proposed the SSD of 3–5 m but analysing the aerial images of an actual fire incident shows that even if the separation distance is > 3.0 m, 97% of the settlement could be at risk in a single fire incident (Wang et al. 2020). Similarly, Jia-qing et al. (2011) admitted that SSDs recommended by existing safety codes (e.g., NFPA 92B) are insufficient to provide required safety under certain circumstances. Currently, due to limited understanding of SSD for waste piles, none of the Swedish County Administrative Boards (Länsstyrelser) have set any specific requirements, directly linking to fire safety (e.g., distance between different heaps or maximum allowable size of heap), in order to issue the license to waste operators (Persson et al. 2014). Numerical simulations also need to be improved, because often various simplified assumptions are used, such as uniform emissivity of unity, isothermal rectangular emitting surface in the radiative models (Sullivan et al. 2003) and considering flame as single point source/cylindrical/cuboidal in shape (Wan et al. 2019). Research is needed for studying the minimum safe separation distance to be maintained between piles for different materials and *one-size-fits-all* approach is futile because of varying heat release rate and soot generation characteristics of different materials (e.g., tires with 32 MJ/kg (Baeyens et al. 2010); RDF with 12 MJ/kg and household waste with 10 MJ/kg (Tambone et al. 2011). It is needed to consider extreme conditions such as, fire whirls, flame merging, high wind speed etc., for determining SSDs.

[9] Use of satellite data can cause under estimation of fire incidents in Sweden, which is a cloudy country (Skogforsk, 2020)

Table 1
MSB waste fires and VIIRS fire anomalies (DbNR).

Year	MSB Incidents	VIIRS DbNR	MSB + VIIRS	Population (P)	$FIPMC_{MSB}$	$FIPMC_{MSB+VIIRS}$
2012	18	22	40	9,555,893	1.9	4.2
2013	24	32	56	9,644,864	2.5	5.8
2014	24	13	37	9,747,355	2.5	3.8
2015	21	18	39	9,851,017	2.1	4.0
2016	21	21	42	9,995,153	2.1	4.2
2017	22	30	52	10,120,242	2.2	5.1
2018	33	25	58	10,230,185	3.2	5.7
Average	23.3	23.0	46.3	9877815.6	AFIPMC = **2.4**	AFIPMC = **4.7**

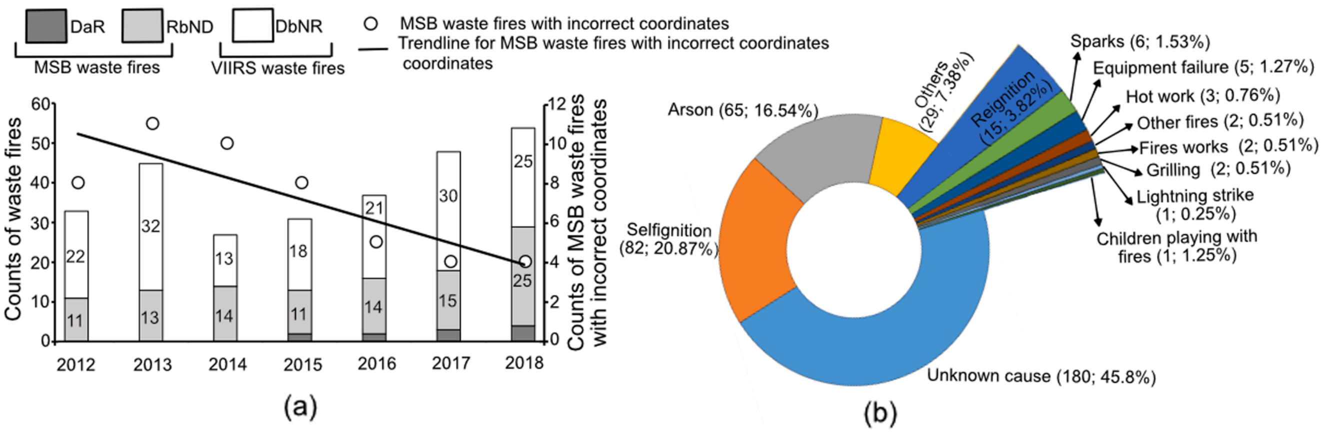

Fig. 4. (a). waste fire incidents (n = 324) and (b). breakdown of causes of waste fire incidents during 2012–18.

Physical design features of waste storage sites are critical for safe and smooth operation of business and to ensure unimpeded access for fire rescue vehicles to all areas in case of emergency and for turning the stockpiles, for isolation of burnt/smouldering fractions. Analysis of satellite images show that the importance of provision of free space along with the perimeter of the storage site and designation of safety zone for firefighter is often overlooked at waste storage sites. The HSB engineering insurance company recommends organizing access roads within and around waste storage site to ensure that no portion of the stockpile should be > 45 m from any access road for conveniently conducting the firefighting operation (HSBEL, 2014), and according to Lönnermark et al. (2018), a clearance of 10–15 m or more should be maintained between two adjacent waste piles.

Placing an obstruction between two stockpiles is one method to simultaneously, reduce the requirement for storage space and to improve the safety against fire incidents. After visualising satellite images and reading the site-specific literature, it is posited that different types of obstructions that are employed between stockpiles are often intended to fulfil the needs other than fire safety, e.g., for preventing intermixing of material with adjacent stockpiles, to keep the pathway clear and to hide the ugliness of messy waste from the line of sight. Fig. 5a is an example in which a single layer of rubber tires is placed all along the perimeter of the piles of shredded rubber tires. This arrangement merely helps in preventing the intermixing of material of two piles but cannot block the thermal radiations between adjacent piles in case of fire incident. Self-heating of styrene-butadiene based rubber tires is a real hazard (Beyler, 2005). Once fire is ignited in a tire storage yard then it is difficult to extinguish and beside releasing toxicants to air, oil spills out from burning tire piles. It is recommended to build earth berms around the burning tire piles to contain the runoff oil from ignition (Stanley and Poole, 1998).

Similarly, Fig. 5c is an example in which the operator of the site placed metal containers, only along the one side of the waste pile that is adjacent to the pathway and no separator is employed along the side of waste pile, which is facing the adjacent waste pile. This suggests that perhaps the purpose of the separators at this site (Fig. 5c) is to keep the pathway clear, and in this scenario, fire can easily propagate from one pile to the other. Likewise, structuring waste bales all along the perimeter of waste sites, though prevents spread of waste to surrounding area under the influence of strong winds and improves external aesthetics of waste sites (see Slotte, (2019b) and Fig. 5g) but in view of fire safety, is not a suitable choice as research shows that low-density-polyethylene (LDPE) wrapped waste bales are highly prone to catch fire (Ibrahim et al. 2015). Secondly, in Fig. 5g, bales are not placed in the form of interlocking rows and can easily collapse and therefore, poses the risk of accelerated flame spread rate in case of fire incident.

Safety against spread of fire at waste sites can be achieved through low thermal conductivity and fire insulation partition blocks (Leiva et al. 2013; Yan et al. 2018). An additional advantage of partition blocks is to readjust the size and number of waste piles separated with walls per unit area as per need. Fig. 5d (a schematic of Fig. 5b) is a design, in which four waste piles are sticked together, back-to-back, with a separation wall, which limits the access of firefighters. The storage design shown in Fig. 5d is only recommended for inert material. For combustible materials, other designs could be considered as shown in Fig. 5e-f. in which stored material is accessible from all sides. The design shown in Fig. 5f is superior to Fig. 5e in view of having provision to store greater amounts of material per unit area of storage space. On the other hand, the design of Fig. 5e could be used when the objective is to store a variety of material fractions. While making any choice on designs, it needs to be considered that the designs shown in Fig. 5e and Fig. 5f, respectively, both require more space than the design in Fig. 5d, and available space is unfortunately something that is limited at many waste sites.

Maintaining a clearance between waste piles and obstruction walls (see Fig. 5e-f) give possibility of first-in-first-out (FIFO) material management from all sides of the waste pile. Considering that the older waste dumps are more prone to self-ignite and have low ignition temperature (Chavan et al. 2019), FIFO is one key strategy, which can help in mitigating the risk of waste fires. At the waste storage site of CemMiljø A/S, both improper design and improper material management (i.e., overfilled waste site and last waste to arrive was used first), resulted in a devastating fire incident costing 1, 764 k€ (Stenis and Hogland, 2011;

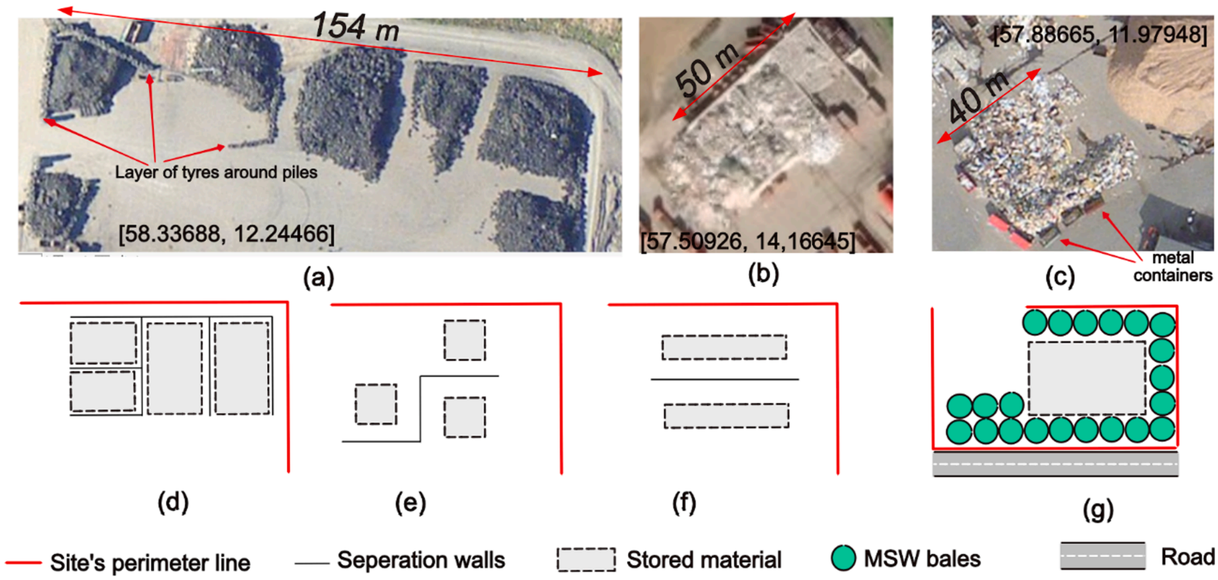

Fig. 5. Techniques for separating waste stockpiles: (a). rubber tires; (b). concrete walls; (c). metal containers; (d) schematic of conventional approach as shown in Fig. 5b; (e-f). proposed arrangement for storage of waste piles and (g). use of bales wrapped with low density polyethylene plastic sheets (LDPE) as separator for waste piles [Source Fig. 5a-c: base map ESRI (ArcGIS Pro 2.5.0), Fig. 5g is a schematic of the waste site described by Slotte, (2019b)].

see Fig. 7a), therefore both design and material management aspects are suggested to be included in the site fire safety plan.

3.3.2. Storage arrangement

It is observed from satellite images that the footprint area of loose compact waste piles within a single waste storage site can vary e.g., from 75 m^2 to 3500 m^2 or higher and organised with varying separation distances (see Fig. 3). Contrarily, few waste sites are found to organise waste piles in the form of a grid (checkerboard format) e.g., at one site (64.78392; 20.03559) 20 m × 20 m piles were organised equidistantly (≈ 7 m apart) in a of 4 × 4 grid. Research shows that burning rate, heat release rate and flame height are tremendously high for multiple discrete combusting fuel sources, (i.e., for a scenario shown in Fig. 6a), especially under conditions when the ratio of *separation distance between fuel-units* to *linear dimension of fuel-units* (SD_{BFU}/LD_{FU}) is less than 1 (Shannon et al. 2020; Zhang et al. 2018; Liu et al. 2013). Therefore, for the scenario shown in Fig. 6a, risk for the ignition of secondary fires is high ($SD_{BFU}/LD_{FU} = 7/20 \approx 0.35$). Randomly oriented heat sources or L-shaped heat sources (as shown in Fig. 5a) also has higher potential to generate fire whirls (Zhou and Wu, 2007; Forthofer and Goodrick, 2011). Burning under such conditions involve strong buoyant forces that are capable to lift and transport firebrands long distances, which have capacity to ignite multiple spot fires in the downwind direction (Manzello et al. 2020), and high radiative heat power of flames can easily ignite adjacently stored material. It is suggested that waste piles should be organised in such a way that SD_{BFU}/LD_{FU} is always greater than unity. Moreover, in view of stark contrast between the heating values of different waste fractions, experimentation is needed for calculation of additional safety factors and for computation of optimized separation distances.

3.3.3. Additional storage practices

Currently, dangerous routines of storing material in the form of large stockpiles and mixing of unlike waste fractions is found common at several storage sites. Research has shown that the risk of self-ignition increases on mixing two different fractions e.g., wood bark and wood

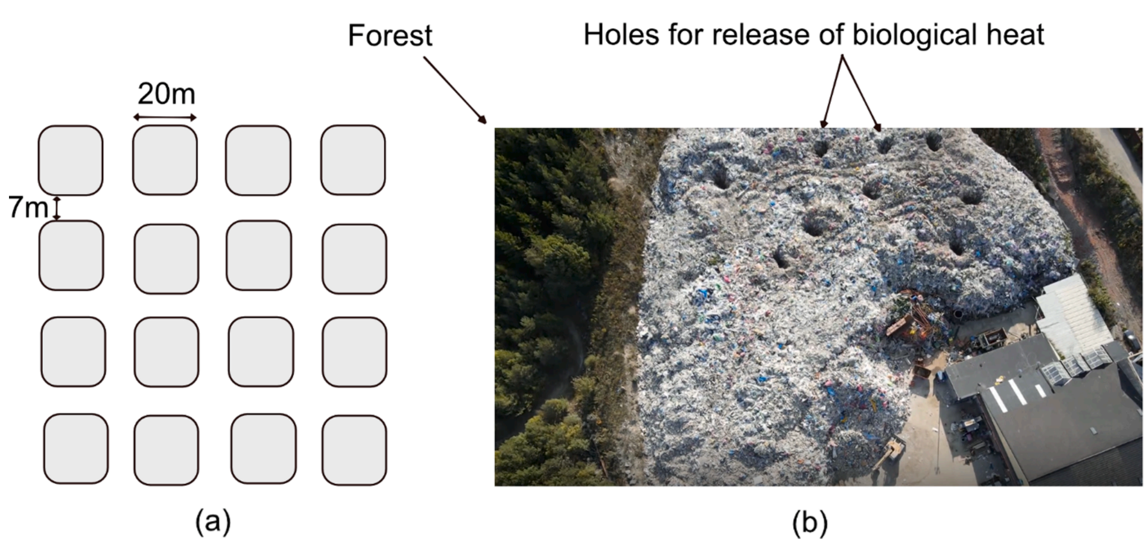

Fig. 6. Waste storage practices (a). schematic of a storage site at which waste piles are organised in the form of a grid; (b). storage site having single large chunk of waste (Kirvesmäki, 2020).

(a) (b)

Fig. 7. Importance of difference of elevation between storage area and that of the access roads, in view of firefighting: (a). stored material is at higher elevation than access road (inset showing a closer view of difficulties in attacking fire) [source: Borup, 2013] and (b). Stored material is at a lower elevation than rest of the site [source Fig. 7b: base map ESRI (ArcGIS Pro 2.5.0)].

chips (Slaven et al. 2011) and hotspots have higher tendency to appear at a region in the stored material where density is not uniform (i.e., at the interface of piles of unlike material fractions) (Hogland and Marques, 2003).

In stored waste, heat is initially produced from physical, chemical, and microbiological processes, and flows, in parallel (not in series) through a complex three phase disperse system, in which, heat easily get transfer through the solid phase and gas phase do not play a limiting role in transfer of heat (Faitli et al. 2015). Therefore, thermal properties of solid phase, i.e., specific heat capacity (capacity of a material to store internal energy) and thermal conductivity (capacity of material to transmit internal energy) are important in view of generation of hotspots. Secondly, considering that heat loss is proportional to surface area and heat production is proportional to volume of fuel (Rein, 2009), it is safer to store material in small multiple piles, instead of one large pile as shown in Fig. 6b. This shows that there is a need to promote safety culture in the waste recycling industry and to study the stress factors that influence waste operators to get inclined towards risky practices.

In case of waste and biofuel fires, it is often inevitable to dig into the stored material to access the base of the fire for isolating the smouldering material. The accessibility of the firefighting team to the smouldering hotspot is difficult, in case storage area is at an elevation higher than (Fig. 7a) or lower than (Fig. 7b) of the access roads. Fig. 7a is a snapshot of a waste fire incident, in which 2000 L of water per minute was applied and where the firefighters gave up after half an hour due to intense combustion heat (Stenis and Hogland, 2011). For the scenario shown in Fig. 7a, there are higher chances for water to penetrate the protective clothing of firefighters and research shows that the moisture that is absorbed in the personal protective clothing of firefighters, internally, from sweat profusion and externally, from water hose, can lead to steam burn injuries (Zainol et al. 2019). Secondly, for extinguishing waste fires, principles used for fighting wildfires can be applied e.g., principle of LCES (Lookout(s), Communication, Escape route(s), Safety zone(s)) is employed in case of wildfires (Gleason, 2004).

Instead of using manmade partitions (concrete walls etc.), vegetation could also be used as a separator between waste piles and even all along the perimeter of waste storage sites. Use of deciduous vegetation is known to hinder spread of fire by acting as a barrier (Astrup et al. 2018) and helps in subsiding the windstorms (Valinger and Fridman, 2011; Eriksson et al. 2019). The lower the speed of wind, the less it would be possible for the wind to penetrate the stored waste pile, and therefore lessen the risks of a smouldering fire to turn into flaming combustion (Buggeln and Rynk, 2002). Such arrangement can help both in reducing the risk of ignition of wildfires caused by waste fires and vice versa.

3.4. Future view

Environmental legislations in relation to waste management are propelling the global recycling business (Barsalou et al. 2018) and waste management now has become one of the fastest growing business with the size of global market of over USD 1 trillion as recorded in 2019 (Gupta and Paranjape, 2020). The growth rate of waste business is directly connected to exponential increase in waste generation. According to the World Bank, the annual generation of waste in 2018 was 2.01 billion tons and expected to raise up to 3.4 billion tons by 2050 (Kaza et al. 2018). It is expected that at global level, the share of uncontrolled disposal will continue to rise at least until 2028, reaching almost 730 million metric tonnes per year (Maalouf, et al. 2020). With increased pressure on the waste management sector, risk of waste fires is expected to increase significantly at global level, as the current rate of growth of waste infrastructure is not concomitant with the rate at which demand for recycling of household and industrial waste is increasing. The dilemma is that international environmental laws and treaties are only promoting the transportation of waste in the name of industrial symbiosis and are not effective for reducing the generation of waste as per EU waste hierarchy (Barsalou et al. 2018). Increased landfill taxes and high demands on recycling of toxics has developed the illegal trade of waste, in which waste is either dumped illegally (Kirvesmäki, 2020) or transported illegally to other countries. For example, about 3.5 million tons (≈ 141,000 truckloads) of illegal waste was seized between January 2015 and May 2016 in Italy (Giorgi, 2018). The overwhelming generation of waste and increased risk of fires at both legal and illegal waste dumps are big hindrances for achieving the sustainable development and circular economy goals at the global level and demands research attention.

There is a need to understand the underlying causes of conflicts between authorities/public and waste operators (e.g., EU petition 0722/2015; EU, 2018) and to develop more clarity in national regulations. Municipalities consider that waste operators are risking the environment due to structural over capacity of waste handling sites. Some waste operators store recyclables in the form of large heaps (Kirvesmäki, 2020) and produce bales with weight exceeding the permittable limit (Slotte, 2019a), and in response, municipalities place bans on the operation of such waste storage sites (Kirvesmäki, 2020; Carlbaum, 2020). However, such municipal restrictions in waste operators' perspective are illegal, causing high financial losses, and leaving negative effects on the waste supply chain (Slotte, 2019b). The waste operators' viewpoint is that they are taking care of the burden of society by handling tons of hazardous and improperly sorted waste every day (Jonasson, 2018). Further, there is need to study the psychological factors that can influence the behavior and decision making of managers at waste companies and risk of waste fires (Ibrahim et al., 2014).

Decrease in availability of recycling drop-off locations and transition from commercial to curbside waste volumes during the COVID-19 pandemic has increased the number of waste fire incidents (Fogelman, 2020). Moreover, in view of a changing climate, in which longer and warmer summers causing droughts are more common, intensity and frequency of waste fires is only expected to increase as waste fires become more common in summer (Ibrahim et al. 2013). In this view, more research is required on fire prevention, detection, and extinction.

Improper sorting of waste is an important cause of spontaneous fires at waste storages. According to an estimate ≈ 4 500 – 7 500 tons of hazardous waste, such as batteries and electronic waste etc., is disposed improperly every year in Sweden (Naturvårdsverket, 2017). Batteries being mixed with ordinary waste are more prone to mechanical shock, short-circuit or chemical reaction, and give rise to large number of dangerous points in the downstream waste management chain for the ignition of waste fires. With expected increase in electronic waste, waste fires are expected to affect the waste management sector even more adversely. Therefore, it is important to facilitate sorting activities by establishing property close recycling centres (RCs), and information about waste sorting should be easy to follow for the visitors of RCs. Moreover, the design layout of RCs should be done in a way that would reduce the *lead-time* of the visitors (*Average time consumed by the visitors in performing the sorting and disposal of waste at RC*) as this factor is known to affect the quality of waste sorting (Ibrahim, 2020b). In past Sundin et al. (2011) discussed the overall layout of recycling centres in Sweden and classified them as (a). one way linear and (b). the square shaped. The Swedish waste management association also issued guidelines for the layout of recycling centres (Avfall Sverige, 2013), but orientation of waste containers with respect to the ramp, which directly control "*lead-time*", are not discussed in detail hitherto. Analyses on the micro-scale (design and management of sites) are needed to further improve the understanding of the contribution of each measure in decreasing the likelihood and consequence of waste fires.

4. Conclusions

It is concluded that the quality of assigning the coordinates of waste fire incidents in the data bank of MSB has appeared to be improved over the years. Further improvements in the data collection routines for waste fire incidents can be made by employing uniform terminologies for describing incidents' "activity/situation". It is very important to be able to find and use the experience from past fires, to learn from them and to implement changes for improved safety. This is necessary for developing appropriate policy guidelines and to efficiently allocate the resources by municipal authorities. It is suggested that the use of satellite data of fire anomalies, in-combination with the use of incident reports (ground-based data), shall help in formalizing more reliable and comprehensive waste fire statistics. Moreover, analysis of the satellite images of waste storage sites shows that existing layout of storage areas and routines followed by waste operators are not optimal, when it comes to mitigate the risk of waste fires. Although, more research is required to develop detailed storage guidelines (e.g., height, volume and footprint area of stockpiles and separation distance between stockpiles) to comprehensively address the problem of waste fires. A very important part of the safety work is to have an updated storage plan, which describes what to store where and how much, and what not to store where. This can also make the basis for the response plan for the fire and rescue service in case of a fire. Much could be achieved by simply following the best practicing guidelines and by improving the layout of storage sites using the design strategies presented in the article and cited references.

The authors are of the opinion that there should be an increased used of satellite data for tracking the occurrence of waste fire incidents. It would help in complementing the ground-based fire data set (collected by rescue services and MSB) and secondly, would support in issuing the early warning for downwind population in view of potential health concerns. Satellite data has the capability to detect and track the transboundary pollutants originating from waste fires in a real-time, however, more research is still required to explore the capability of satellite data for the development of a national near-real-time waste-fire inventory system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by KK-stiftelsen [grant number 817-2.1.9, 2017] and Åforsk-stiftelsen [21-106].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.02.004.

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