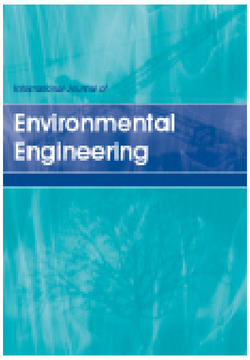


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# Mitigating the risk of secondary fires at MSW bale storage sites

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# Mitigating the risk of secondary fires at MSW bale storage sites


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**Abstract:** The article discusses the suitability of several existing empirical models for determining the safe separation distances (SSDs) for waste fuels. Contour plots of SSDs are generated based on isotropic thermal radiation model for safely storing municipal solid waste (MSW) bales under different storage settings and the plots can be employed for routine hazard assessment purposes. Further, experimental design technique was employed, and orthogonal test matrices were generated to conduct the experiments for studying the combustion dynamics of the primary fire under the influence of storage settings of surrounding fuel units. The main and interaction effects of various storage parameters (e.g., height of adjacent fuel sources, clearance between fuel sources and array size) on the response variables (flame height and burn out time) were studied. A list of appropriate measures for minimising the risk of secondary fires at MSW bale storage sites is provided.

**Keywords:** bale storage; secondary fires; waste fires; bale fires; waste fuels; safe separation distance; safety distance; interactive burning; abreast flames; industrial fire safety; flame height; burn out time; *BOT*.

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**Biographical notes:** Muhammad Asim Ibrahim is currently serving as a researcher at Linnaeus University, Sweden and leading several national and international projects that has focus on risk of waste fires. His PhD thesis is on quanitification and mitigation of risk of waste fires. He is considered as an authority on this subject and his research work got attention on Swedish state television and radio several times. He completed his Master's in Process Engineering from Pakistan Institute of Engineering and Applied Sciences (PIEAS) and earned his Bachelor's in Chemical Engineering from the University of the Punjab, Lahore, Pakistan.

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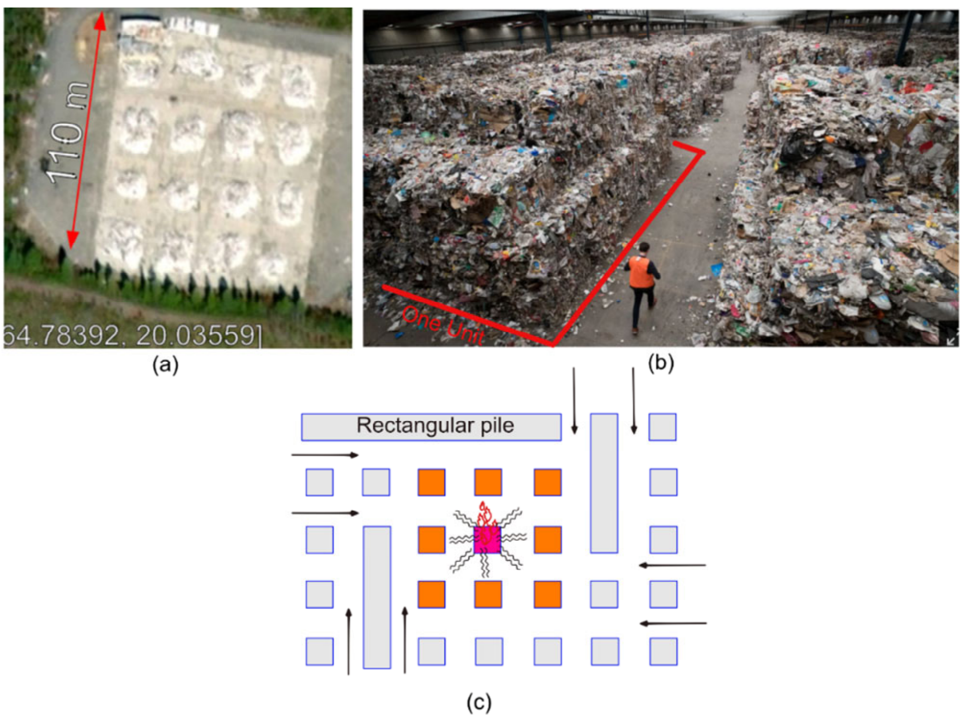
This paper is a revised and expanded version of a paper entitled 'Organization of industrial storages in view of risk of fire accidents' presented at LNU-EcoTech 2016, Kalmar, Sweden, 21–23 November 2016.

## 1 Introduction

Waste management sector is growing worldwide at a notable rate and expected to achieve a global market size of US$435 billion by 2023 (Redling, 2018). Particularly in EU territory, various legislative instruments, such as Landfill Directive (1999/31/EC), Battery Directive (2006/66/EC), Directive on End-of-Life Vehicles (2000/53/EC), Waste Framework Directive (2008/98/EC), and most importantly, priority action plan of EU to secure the supply of critical materials, have amplified the flux of waste recycling streams. However, the existing recycling infrastructure lacks the capacity to safely handle and store the waste and recyclables (Ibrahim, 2020a). Due to structural overcapacity of waste handling sites and vacuum of science-based storage guidelines, waste operators often adopt careless storage routines, which has increased the frequency of high intensity waste fire incidents (Ibrahim, 2020b). In view of escalating risk of waste fires, authorities often believe that waste operators are performing environmental crimes by storing large amount of waste in an unsecure way (Kirvesmäki, 2020), and on the other hand, waste operators describe such authoritative checks as misuse of authority (Slotte, 2019). This growing conflict motivates to do more research for the development of science-based storage guidelines and safety distances to be maintained at waste sites. According to Swedish environmental protection agency, there is need to enhance the understanding of risk of waste fires and to develop performance-based safety protocols for minimising the risk of spread of waste fires (Naturvårdsverket, 2021).

Waste and recyclable fires are lethal, extremely expensive, pose high social and environmental burden (Ibrahim et al., 2013; Ibrahim, 2020b), and engage substantial firefighting resources, e.g., 150 firefighters participated in a massive fire in a paper recycling facility in UK (Firehouse, 2021). Generally, it is difficult to suppress waste fires and there are several examples in which, waste fires led to complete destruction of recycling facilities (IFW, 2020; Sharman, 2016). Several studies in past, discussed the concern on waste fire incidents, e.g., in the context of UK, Austria, Germany (Nigl et al., 2020), USA (Fogelman, 2018), Italy (Mazzucco et al., 2020), Thailand (Wiwanitkit, 2016), and Nordic region (Ibrahim et al., 2013; Ibrahim, 2020b; Mikalsen et al., 2021). It is established that waste fires are common at all stages of waste recycling chain (Ibrahim, 2020b). In Sweden, about 200 waste fires incidents are reported every year and the ratio between indoor and outdoor waste fires is 1:4 (Persson et al., 2014), showing that both, indoor and outdoor waste fires are common.

**Figure 1** Waste and recyclable storage, (a) outdoors (b) indoors (Lucas and Preiss, 2019) (c) schematic showing sequence of events for generation of group fires (stage-1 to stage-4) (see online version for colours)




Notes: Figure 1(a) is used herein under license and is allowed to be used by the ESRI for publication in the article. The permission to use Figure 1(a) for publication was granted by Lucas (senior news reporter at The Age) on 20th August 2021.

*Source:* Figure 1(a) is base map ESRI (ArcGIS Pro 2.5.0)

## *1.1 Theoretical aspects of waste fires propagation*

Both at indoor and outdoor storage sites, waste materials are commonly organised as arrays of cubic staking of bales and loose-compact stockpiles (mentioned as fuel units here onwards, see Figure 1), and the choices made for array size, clearance between fuel units, foot-print area, and height of fuel units, vary drastically among waste operators, which in some instances induce high risk for the initiation of group fires. A recent waste fire incident in Halmstad, Sweden is a typical example of group fires in waste stockpiles (Magnusson et al., 2021). Currently, little is known about isolated effect and interaction effect of storage parameters (i.e., array size, clearance between fuel units, foot-print area, and height of fuel units) on combustion dynamics of primary fire and the risk for ignition of secondary fires.

There is sequence of events through which a single fire turns into an aggressive group fire [see Figure 1(c)]. In the *stage-1*, thermal radiations liberated from an initial single fire (primary event), dries out and makes it easier for the adjacent layer of fuel units to get charred and ignite. In the *second stage*, a pressure gradient is generated between the central fire and the surrounding fire units due to restricted air entrainment in the centre of combustion zone, which causes inward tilting and even merging of multiple flames into a single large swirling flame. In the *third stage*, air entraining into the combustion zone from the spacing between the fuel units, standing at the outer periphery (that are not ignited yet), adds additional vorticity in the fire plume and gives birth to fire whirl, which further enhances heat release rate and heat feedback to the next layer of fuel units. The foot-print area, characteristic length and height of the adjacent fuel unit control the air entrainment and buoyancy of the combustion zone [especially while using a combination of rectangular and square stockpiles, which is commonly practiced in waste industry, see Figure 1(c)]. *Lastly*, this highly buoyant plume has ability to generate spot fires at large distances and leads to secondary fires (e.g., agricultural fires, wildfires, urban fires, or new waste fires) (Chaos, 2017; Ibrahim, 2020b). Generally, the performance of all these four stages (fire initiation, fire interaction/merging, fire intensification and fire propagation) strongly depends upon factors such as: density and distribution of fuel units (i.e., array-size and clearance between fuel units), and size and power of each fire source (i.e., footprint area and heating value).

The current understanding about the strict physical conditions under which multiple fires start interacting is not adequate (Satoh et al., 2008, 2014a, 2014b), which limits to make informed decisions for maintaining the save separation distance between units of waste fuels. For example, Jia-qing et al. (2011) argued that safe separation distances (SSDs) recommended by existing safety codes (e.g., NFPA 92B) are insufficient to provide required safety under certain circumstances. A review of literature on fire-interaction shows that interactions of abreast flames have mostly been studied using regularly spaced, limited number of optically thin fuel sources, often of size ranges up to 10–15 cm, located on a horizontal plane (Liu et al., 2017; Fan and Tang, 2017) or alternately, jet flames were used (Kuwana et al., 2016; Ma et al., 2018) and mostly focusing on exploring: flame merging probability (Ma et al., 2018), flame merging behaviour (Huaxian et al., 2018; Ji et al., 2016), effect on mass loss rate (Liu et al., 2017; Ji et al., 2016), burn out time (*BOT*) (Liu et al., 2007, 2009, 2013), variation in flame structure (Sugawa and Oka, 2003), radiative heat flux (Weng et al., 2015) and pulsation frequency of fires (Fukuda et al., 2006). Researchers have proposed diverse models and varying critical conditions for flame merging, e.g., maintaining centre to centre distance $\leq 40$ cm between two fire sources, having ratio of centre to centre distance of fire sources to flame height (*FH*) in range of 0.29–0.34 (Liu et al., 2007), having ratio of distance between adjacent fire sources to diameter of fire source in range of 0.1 to 0.5 (Schälike et al., 2013) or having ratio of distance between adjacent fire sources to diameter of fire source $\leq 2$ times the diameter of fuel source (Putnam and Speich, 1963), can leads to flame merging. The most of these existing flame-merging models are valid only for specified conditions (Finney and McAllister, 2011; Shanon et al., 2020) and restricted to the visible merger of flames (Lu et al., 2015; Ji et al., 2021), therefore, cannot be employed for determining SSD. Because from practical point of view, the outward radiation flux from group fires is a more reliable criteria for determining safety distances but is rarely studied in past and demands research attention (Liu et al., 2017). This article focuses on revisiting the various thermal radiative flux and surface emissive power (SEP) models, in the context of waste fuels and to develop the screening level safety distance guidelines for municipal solid waste (MSW) bale storage sites. Further, experiments were conducted to study the effect on the burning conditions of the primary fire source and risk of secondary fires, under the influence of storage settings of the surrounding fuel units.

## 2 Material and methods

### *2.1 Outward radiative heat flux from the fire source and SSD*

Simple to complex models were developed in the past for determining the outward radiative flux received from a primary fire source and in these models, initial fire source was either assumed as a point source (Fleury, 2010; Jia-qing et al., 2011; Liu et al., 2017), as a cylindrical source (Dayan and Tien, 1974; Ufuah and Bailey, 2011; Weng et al., 2015), as a rectangular source (Fleury, 2010) or as a quadric source (Chaos, 2017). Table 1 presents the key characteristics of common radiative flux models.

**Table 1** Characteristics of common radiative flux models

| *Model* | *Characteristics* |
|---|---|
| Point source | • Simplest configurational model and used for a range of applications (Fleury, 2010).<br>• The point source model is a most suitable assumption, while target is at a significantly large distance from the fire (Beyler, 1999; Fleury, 2010)<br>• The prediction made by point source model is within 5% of the measured incident heat flux, when $L/D > 2.5$ (Modak, 1977), where '$L$' is distance of target from the centre of fire and '$D$' is fire diameter (Fleury, 2010).<br>• The overall average error introduced by point source model is less than 22% (Fleury, 2010). |
| Cylindrical source | • It is assumed that thermal radiation is emitted from the surface of the cylinder (Fleury, 2010).<br>• Cylindrical models are mostly developed based on experimental data of liquid pool fires (Fleury, 2010).<br>• Several cylindrical models are proposed by researchers in past and each works well only under certain condition, e.g., the cylindrical model of Dayan and Tien (1974) is applicable for $L/r \geq 3$ ('$L$' is distance of target from the centre of fire and '$r$' is radius of fire).<br>• In the model of Shokri and Beyler (1989) effective emissive power is defined in terms of effective pool diameter, which is a major source of uncertainty in determining the outward radiative flux.<br>• The overall error in the cylindrical models proposed by Dayan and Tien, Shokri and Beyler, and Mudan is 35%, 50% and 228%, respectively (Fleury, 2010). |

**Table 1** Characteristics of common radiative flux models (continued)

| *Model* | *Characteristics* |
|---|---|
| Rectangular source | • Flame is approximated as two perpendicular intersecting planes.<br>• Several rectangular models exist, and each operates well only under certain conditions, e.g., rectangular model of Seeger (1974) is only valid for vertical targets (Fleury, 2010) and the model of Chaos (2017) is valid only for free burn fire of up to 50 MW.<br>• The overall average error introduced by rectangular model of Fleury (2010) is 42%. |

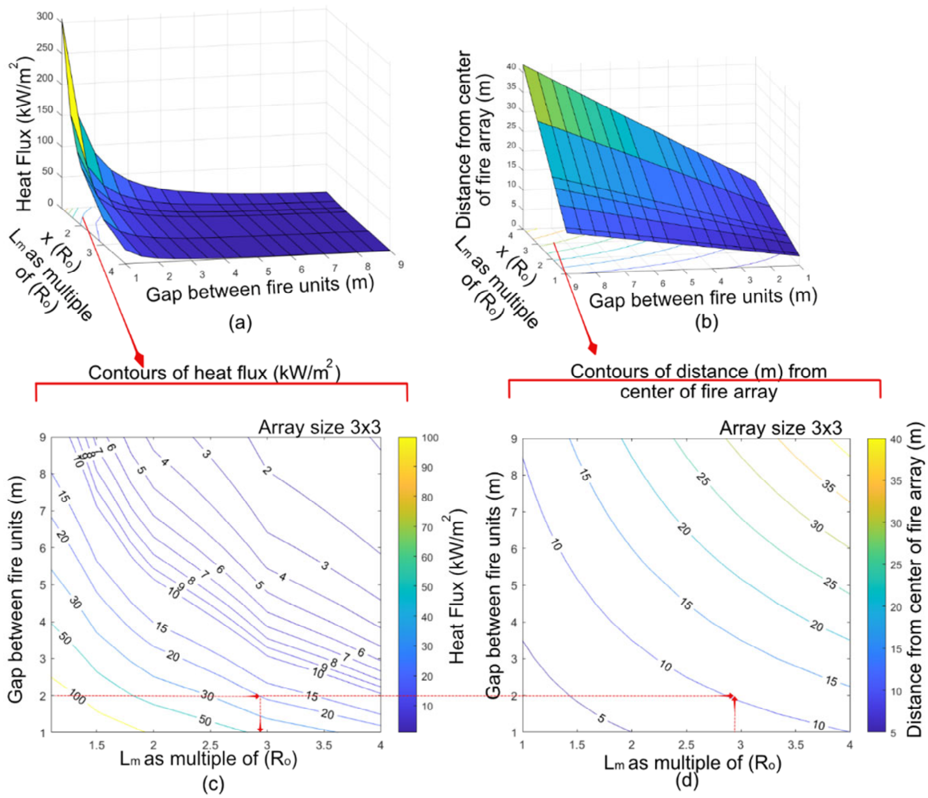
A comparative study of several existing models shows that the isotropic model is the most accurate and reliable for a range of experimental conditions (Fleury, 2010; Jia-qing et al., 2011; Ingason and Lönnermark, 2011). Advanced models try to accommodate more physical details but at the expense of higher uncertainty (Fleury, 2010). According to the point source model, critical radiative flux, required for pilot ignition of target fuel situated at a distance $R$ meters from the point source is $\dot{q}'' = \dot{x}_r Q / 4\pi R^2$. Where $\dot{Q}$ is total heat release rate from the fire (kJ/s) and $x_r$ is the radiative fraction received by the target. Applying this analogy of isotropic fire source on a fire array, Liu et al. (2017) developed an advanced empirical model equation (1) for determining the SSD from an array of fire sources, where $\dot{q}_m'' / \dot{q}_o''$ is the ratio of radiative flux from the fire array to the individual fire source and $R_0$ is radius of fire array. The parameter $r_s$ is ratio of fuel surface area to fire array area, $n$ is number of fuel sources in a single row or column, $d$ is diameter of single fuel source and $D$ is centre to centre distance between two adjacent fuel sources.

$$\dot{q}_m'' / \dot{q}_o'' = 2.360\, r_s \left( L_m / R_o \right)^{-2} \tag{1}$$

$$r_s = \frac{n^2 \cdot (\pi/4) \cdot d^2}{\left[ d + (n-1)D \right]^2} \tag{2}$$

The empirical model of Liu et al. (2017) is based on the experiments in which fire arrays of various size ranges (3 × 3 to 6 × 6) were tested and the power of each fire source was 37 kW/m$^2$. This correlation is an excellent fit of experimental data ($R^2 = 0.966$) and valid for $R_0/L_m < 1$ (Liu et al., 2017). In this study, the empirical model of Liu et al. (2017) was extended for determining SSD for safely storing MSW bales. In equation (1), the parameter $L_m$ was selected as multiples of Ro (i.e., 1.1 $R_o$, 1.5 $R_o$, 1.8 $R_o$, 2.0 $R_o$, 3.0 $R_o$, 4.0 $R_o$), heat release rate per unit area (HRRPUA)[1] $q_o$ was supplied as 200 kW/m$^2$ (Ibrahim et al., 2015), and the separation distance between MSW bales was set as 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5 and 9.0 m. The values of the parameter $r_s$ depends upon the combination of array size and separation distance and supplied accordingly in equation (1). The values of SSD were calculated for a range of combinations of array sizes (3 × 3 to 9 × 9) and the separation distances between fire units (see Figures 2 and 6). Firstly, 3D surface plots of heat flux kW/m$^2$ ($q_m$) [Figure 2(a)] and the distance from the centre of the fire array ($L_m$) as a multiple of $R_o$ [Figure 2(b)], were plotted for a certain array size. Afterwards, a pair of 2D contour plots [Figures 2(c) and 2(d)] that have common $x$-axis, were extracted from the 3D surface plots. The arrows shown in Figure 2 demonstrates the methodology for determining the SSD for MSW bales organised in a 3 × 3 array. Firstly, the values of the desired separation distance between fuel units are selected from the ordinate of Figure 2(c) (in this case 2 m is selected) and *secondly*, a certain heat flux level is assumed as critical for ignition of target fuel [in this case 20 kW/m$^2$ is selected, see the iso-contour line corresponding to 20 kW/m$^2$ in Figure 2(c)]. The point of intersection of "gap between fire units" [ordinate of Figure 2(c)] and "selected critical heat flux level for ignition of target fuel" [iso-contour line in Figure 2(c)], leads to determine the corresponding value of the abscissa on Figure 2(c) [i.e., the distance from the centre of the fire array ($L_m$) as a multiple of $R_o$]. Afterwards, this value of abscissa ($L_m$), which is determined from Figure 2(c) is supplied to abscissa ($L_m$) of Figure 2(d) and its point of intersection with the value of 'the gap between fire units' (in this case 2 m is selected) leads to determine the SSD in meters for a particular storage setting (10.5 m is determined in this case). The additional pairs of 2D contour plots for various settings of array size (i.e., 5 × 5, 7 × 7 and 9 × 9) are presented in Figures 6(a)–6(b), 6(c)–6(d) and 6(e)–6(f). Besides these contour polts, other empirical correlations related to outward radiative flux from fire source and surface emission power are discussed in the context of storage of MSW bales.

**Figure 2** Outward radiative flux and SSD for MSW bale storage (see online version for colours)




## 2.2 Storage settings and fire interaction

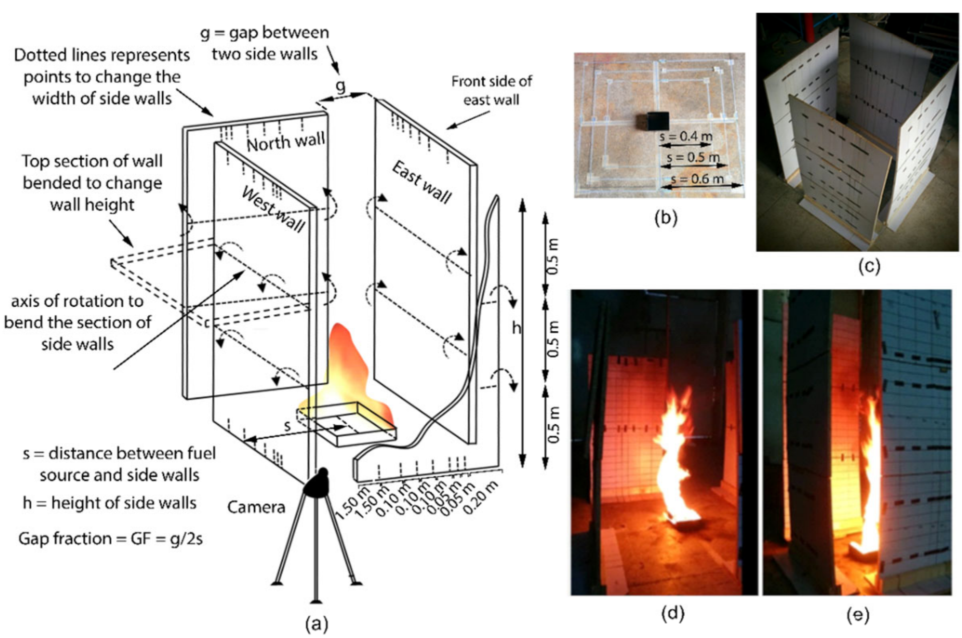
There could be a single fire source or an array of fire sources posing hazard for ignition of adjacent fuel units. In this view, dynamics of a single fire source (*scenario-1*, Figure 3) as well as of array of fire sources (*scenario-2*, Figure 4), under the influence of storage settings (i.e., clearance between fuel units, and height and footprint area of adjacent fuel units) was investigated. In this study, the focus is not to study the effect of chemical properties of waste fuels on the combustion dynamics but to explore the effect of the physical settings of fuel units, therefore, standardised kerosine fuel sources were employed. The adjacent fuel units of varying height and width were simulated with the help of specially designed, multi-parts, four structured walls [*north, south, east and west walls*, see Figures 3(a) and 3(c)] and each structured wall comprises of 24 (8 vertical cut × 3 horizontal cut) slices, with a possibility for each slice to clamp/unclamp. The width of each slice was unique and adjusted so that it would be possible to study the effect of the parameters to be investigated on the response variables (*FH* and *BOT*) as per experimental design settings shown in Figure 5. Tables 2 and 3 present the central composite design (CCD) settings employed for phase-1 (*corresponding to the scenario-1*) and phase-2 (*corresponding to the scenario-2*) of experiments. In the phase-1 of experiments, three parameters:

a distance between two adjacent structured walls ‘*g*’

b height of the structured walls ‘*h*’

c gap fraction ‘*GF*’ (dimensionless measure of the width of the adjacent fuel units – the ratio of clearance between two adjacent structured walls ‘*g*’ to the distance between two opposing structured walls ‘2*s*’ [see Figure 3(a)]), were varied at three levels as per CCD shown in Figure 5.

**Figure 3** Experimental arrangement for studying the effect of surrounding structures on single fire (phase-1), (a) schematic of experimental setup (b) marking showing three level positioning of side walls (c) actual experimental setup (d)–(e) snapshots of experiments (see online version for colours)



In the phase-2 of experiments, parameter '*h*' was set as 1.5 and '*s*' as 0.6, and three parameters:

a '*GF*'

b dimensionless spacing between fire units '$D^*$'(ratio of centre-to-centre distance between adjacent fire sources to the diameter of single fire source)

c array size '*N*', were varied at three levels as per CCD shown in Figure 5.

The values of parameters *h* (1.5) and *s* (0.6) for phase-2 of experiments were selected based on the results of interaction effect of parameters *s* and *h* ($I_{s,h}$) obtained during phase-1 of experiments, which shows that this combination of *s* and *h* (higher-level settings) promotes *FH* (further discussed in Subsection 3.3). In practice, the value of parameter *GF* could have values between zero (i.e., no gap between adjacent structured walls) and one (i.e., no walls). In this study, a more realistic range was selected for the parameter *GF* (0.25, 0.50 and 0.75), which closely represent the reality. The values of parameters *N* (array size) and $D^*$ were selected in view of the practical constraints for performing experiments, such as size of fuel pans and available space between opposing structured walls. Based on the findings of preliminary test experiments, parameter *h* varied from 0.5 m to 1.5 m, the lower limit corresponds to maximum *FH* of single fire source under isolated burning conditions and upper limit corresponds to fire whirl height, achieved during intense fire interaction.

**Figure 4** Experimental arrangement for studying the effect of surrounding structures on a fire array (phase-2), (a) schematic of experimental setup (b)–(e) snapshots of experiments (f)–(g) thread-gauze arrangement (see online version for colours)

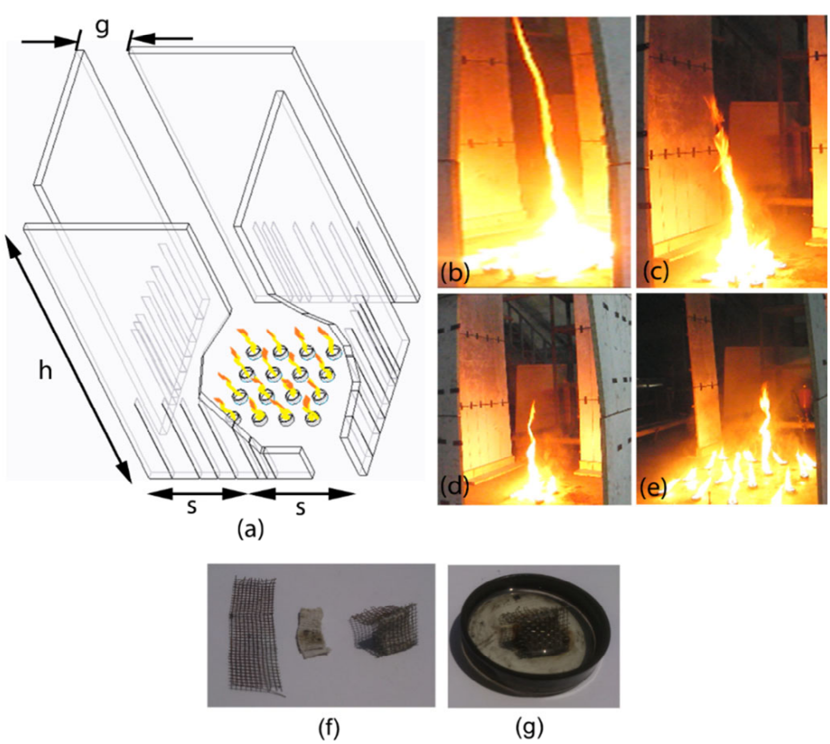
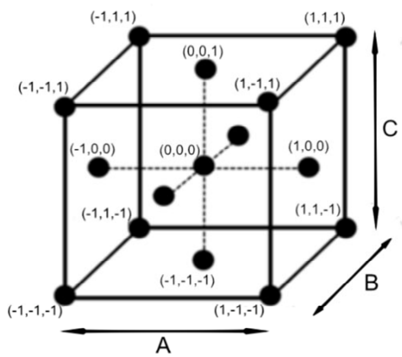


**Figure 5** Central composite design settings of phase-1 and phase-2 experiments and parameters settings




| Parameters | For Phase-1 | For Phase-2 |
|---|---|---|
| A | GF | GF |
| B | s | D* |
| C | h | N |

| Settings | For Phase-1 | | | For Phase-2 | | |
|---|---|---|---|---|---|---|
| | GF | s | h | GF | D* | N |
| -1 | 0.25 | 0.4 | 0.5 | 0.25 | 2 | 2x2 |
| 0 | 0.50 | 0.5 | 1.0 | 0.50 | 3 | 3x3 |
| +1 | 0.75 | 0.6 | 1.5 | 0.75 | 4 | 4x4 |

GF = gap fraction = g/2s
s = gap between two adjacent structured walls
h = height of structured walls
N = Array Size

D*= ratio of center to center diference between two fire sources to dia of fire sources

## 2.3 Orthogonal test matrices

Tables 2 and 3 are orthogonal test matrices for phase-1 and phase-2 of experiments in which factor columns are linearly independent from each other and ensures the complete separation of each factor's effect on the response variable (i.e., *BOT* and *FH*). Most studies done in the past do not follow orthogonal test plan and accompanies the problem of collinearity, i.e., the effect of parameters blends with each other. For example, Zhang et al. (2018) concluded that flame merging is more dependent on flame spacing than the fire array size $n \times n$ but, in that study, it was not possible to calculate the interaction effects as the data did not originate from orthogonal test plan.

## 2.4 Main effect and interaction effect

The main effects of parameters *GF*, *s*, *h*, *N* and $D^*$ show the average change in *BOT* and *FH*, as these parameters are changed from the low-level to the high-level settings. Mathematically, the main effect (*M*) of any parameter *P* on the response variables [i.e., burn out time ($BOT_i$) and flame height ($FH_i$)], is defined as (Antony and Capon, 1998; Andersson, 2012):

$$M_p = \left[\left(\sum_{i=1}^{l} BOT_{i(+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} BOT_{i(-1)} \Big/ l\right)\right] \tag{3}$$

$$M_p = \left[\left(\sum_{i=1}^{l} FH_{i(+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} FM_{i(-1)} \Big/ l\right)\right] \tag{4}$$

where *P* could be any parameter *GF*, *s*, *h*, $D^*$ or *N*. Here, *l* is number of times a parameter is set at a certain setting level, and the subscript (+1) and (–1) corresponds to higher and lower-level settings (see Figure 5).

**Table 2** Orthogonal test matrix for phase-1 of experiments

| *Sr. no.* | *Parameters* | | | *Setting levels l* | | |
|---|---|---|---|---|---|---|
| | *GF* | $D^*$ | *N* | *GF* | $D^*$ | *N* |
| 1 | 0.25 | 2 | 2 × 2 | –1 | –1 | –1 |
| 2 | 0.75 | 4 | 4 × 4 | 1 | –1 | –1 |
| 3 | 0.25 | 2 | 2 × 2 | –1 | 1 | –1 |
| 4 | 0.75 | 4 | 4 × 4 | 1 | 1 | –1 |
| 5 | 0.25 | 2 | 2 × 2 | –1 | –1 | 1 |
| 6 | 0.75 | 4 | 4 × 4 | 1 | –1 | 1 |
| 7 | 0.25 | 2 | 2 × 2 | –1 | 1 | 1 |
| 8 | 0.75 | 4 | 4 × 4 | 1 | 1 | 1 |
| 9 | 0.50 | 3 | 3 × 3 | 0 | 0 | 0 |
| 10 | 0.25 | 2 | 2 × 2 | –1 | 0 | 0 |
| 11 | 0.75 | 4 | 4 × 4 | 1 | 0 | 0 |
| 12 | 0.50 | 3 | 3 × 3 | 0 | –1 | 0 |
| 13 | 0.50 | 3 | 3 × 3 | 0 | 1 | 0 |
| 14 | 0.50 | 3 | 3 × 3 | 0 | 0 | –1 |
| 15 | 0.50 | 3 | 3 × 3 | 0 | 0 | 1 |

Notes: *GF* = gap fraction; $D^*$ = ratio of centre to centre difference between two fire sources to dia. of fire sources; *N* = array size.

**Table 3** Orthogonal test matrix for phase-2 of experiments

| *Sr. no.* | *Parameters* | | | *Setting levels l* | | |
|---|---|---|---|---|---|---|
| | *GF* | *S* | *h* | *GF* | *S* | *h* |
| 1 | 0.25 | 0.4 | 0.5 | –1 | –1 | –1 |
| 2 | 0.75 | 0.6 | 1.5 | 1 | –1 | –1 |
| 3 | 0.25 | 0.4 | 0.5 | –1 | 1 | –1 |
| 4 | 0.75 | 0.6 | 1.5 | 1 | 1 | –1 |
| 5 | 0.25 | 0.4 | 0.5 | –1 | –1 | 1 |
| 6 | 0.75 | 0.6 | 1.5 | 1 | –1 | 1 |
| 7 | 0.25 | 0.4 | 0.5 | –1 | 1 | 1 |
| 8 | 0.75 | 0.6 | 1.5 | 1 | 1 | 1 |
| 9 | 0.50 | 0.5 | 1.0 | 0 | 0 | 0 |
| 10 | 0.25 | 0.4 | 0.5 | –1 | 0 | 0 |
| 11 | 0.75 | 0.6 | 1.5 | 1 | 0 | 0 |
| 12 | 0.50 | 0.5 | 1.0 | 0 | –1 | 0 |
| 13 | 0.50 | 0.5 | 1.0 | 0 | 1 | 0 |
| 14 | 0.50 | 0.5 | 1.0 | 0 | 0 | –1 |
| 15 | 0.50 | 0.5 | 1.0 | 0 | 0 | 1 |

Notes: *GF* = gap fraction; *S* = gap between two adjacent structured walls; *h* = height of structured walls.

The two-way interaction of parameter-A with respect to parameter-B $(I_{P_A,P_B})$ shows the way the response to a change in parameter-A ($P_A$) is affected by the setting of the parameter-B ($P_B$) and mathematically is a difference between "the effect of $P_A$, when $P_B$ is at higher level setting" and "the effect of '$P_A$', when '$P_B$' is at low level setting." Mathematically, the interaction effect ($I$) of any parameter $P$ on the response variables [i.e., burn out time ($BOT_i$) and flame height ($FH_i$)], is defined as follows (Antony and Capon, 1998; Andersson, 2012).

$$I_{P_A,P_B} = \left[\left(\sum_{i=1}^{l} BOT_{i(P_A+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} BOT_{i(P_A-1)} \Big/ l\right)\right]_{P_B+1} - \left[\left(\sum_{i=1}^{l} BOT_{i(P_A+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} BOT_{i(P_A-1)} \Big/ l\right)\right]_{P_B-1} \quad (5)$$

$$I_{P_A,P_B} = \left[\left(\sum_{i=1}^{l} FH_{i(P_A+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} FH_{i(P_A-1)} \Big/ l\right)\right]_{P_B+1} - \left[\left(\sum_{i=1}^{l} FH_{i(P_A+1)} \Big/ l\right) - \left(\sum_{i=1}^{l} FH_{i(P_A-1)} \Big/ l\right)\right]_{P_B-1} \quad (6)$$

where $l$ is number of times a parameter is set at a certain setting level, and the subscript (+1) and (–1) corresponds to higher and lower-level settings.

## *2.5 Description of fuel sources and ignition methodology*

In the phase-1 of all experiments, 200 ml (≈ 0.16 kg) of kerosine oil was employed in a metallic pan (16 cm × 16 cm × 5 cm). Under isolated burning conditions, average *BOT* of 381 sec was achieved and the overall power of the fire source was found to be 18.43 kW ([heating value of kerosine; 43.1 (MJ/kg)] × [mass loss rate; 0.00042 kg/sec]). The motivation for employing kerosine in phase-1 and phase-2 of experiments was to have fuel sources of consistent power in all the experiments, which is difficult to achieve for solid waste fuels, e.g., because of varying degrees of impurities and particle size distributions, there is always high risk to have varying HRR among different solid waste samples. Secondly, the focus in this study was not to investigate the chemical properties of waste fuels but to study the effect of the physical settings of fuel units on the combustion efficiency, in general.

In phase-2 of experiments, 20 ml of kerosene oil in glass dishes (each of 5 cm diameter) was employed to have abreast flames of consistent power. A 'V-shaped' thread-gauze arrangement was developed by wrapping a piece of cotton (1 cm × 2 cm) in metallic wire gauze (2 cm × 6 cm) and placed in the fuel pans as 'inverted-V' [see Figures 4(f)–4(g)]. This arrangement helped in achieving the differences in ignition time of flames <10 sec, during all experiments of phase-2. In past studies, controlling the differences in ignition times of abreast flames within 10 s was considered acceptable, while studying fire interaction of abreast flames (Liu et al., 2009).

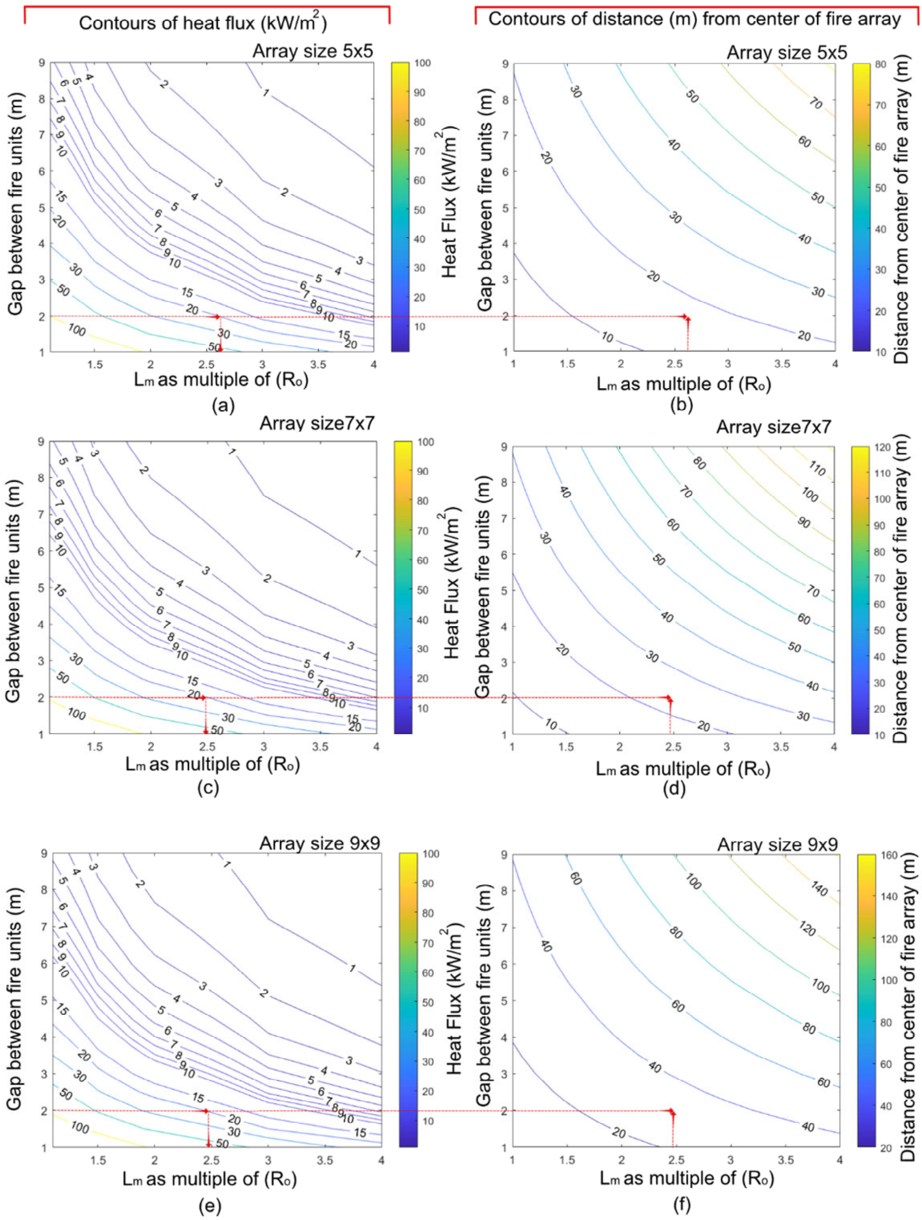
A digital video camera was used to record all the experiments and videos were rendered at the rate of 1 frame/sec. Camera was positioned at an elevation of 61 cm from ground and at a distance of 183 cm from the centre of fire array. Maximum *FH* and *BOT* were used to characterise the fire performance. The values of maximum *FH* were measured by image processing in IMAGEJ 1.49v. In the first step, a reference scale for pixels in a video frame was developed by supplying the software the distance between two selected pixels for which separation distance is already known (i.e., the height of the structured wall) and in the second step, *FH* in a certain frame was determined using that reference scale.

## 3 Results and discussion

### *3.1 Critical SSD*

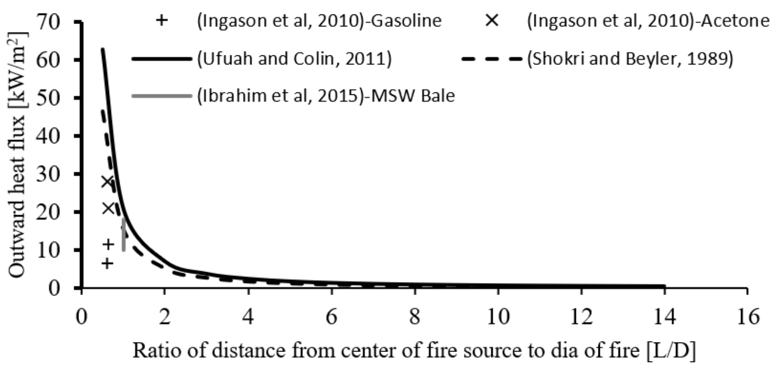
Although the simple isotropic thermal radiation model of Liu et al. (2017) do not consider the effect of wind, shape and size of flame, view factor between the source and the target, and thermal radiations that are attenuated by air moisture, but is still reliable. The isotropic thermal radiation model, in general, holds average percentage error of less than 18%, while the advance models are known to introduce error up to 200%, when compared with the experimental data (Fleury, 2010). Similarly, Ingason and Lönnermark (2011) concluded that the point source model gives a better description of the distance dependency of the radiation reduction in compared to advance models that uses view factor. Therefore, in view of better accuracy of point source model, contour plots shown in Figure 6 can be used to develop screening level safety guidelines for storage of MSW bales. The SSD calculations in this study are more useful than the existing generalised storage recommendation, in which effect of array size was not considered. For example, the minimum recommended SSD between two stacks of waste bales is 5 m (Lönnermark et al., 2019) and according to WISH, the SSD between one bale-stack to the adjacent bale-stack is 9 m for a 5 m wide stack, 11 m for a 7 m wide stack and 12 m for a 9 m wide stack, but the experimental details and the value of critical heat flux assumed for ignition was not provided. Contrary to these existing guidelines, Figures 2 and 6 are more user friendly and provides broad range of possibilities to waste operators to determine SSD based upon their preferred storage setting and available space at their storage site. For example, Figures 2 and 6 show that for array of bales with inter-bale clearance of 2 m, the adjacent array (target fuel) must be situated at a distance >10.5 m for 3 × 3 array, >17 m for 5 × 5 array, >24 m for 7 × 7 array, and >30 m for 9 × 9 array (assuming 20 kW/m$^2$ as critical heat flux). Similarly, the SSD for adjacent array (target fuel) is >12 m for 3 × 3 array, >18 m for 5 × 5 array, >27 m for 7 × 7 array, and >35 m for 9 × 9 array (assuming 15 kW/m$^2$ as critical heat flux). In Figures 2 and 6, waste operators can select any value of critical heat flux, e.g., between 10–15 kW/m$^2$ for determining the SSD. In past, a minimum incident thermal radiation flux of 10 kW/m$^2$ (Lönnermark et al., 2019; WISH, 2020) and in some cases 15 kW/m$^2$ (Chaos, 2017; Tewarson, 2002) was considered as an accepted standard for ignition of waste stacks and other combustibles. The critical heat flux for ignition of different types of woody biomass also lies in this range, such as western red cedar (13.3 kW/m$^2$), Redwood (14 kW/m$^2$), Radiata Pine (12.9 kW/m$^2$), Douglas Fir (13.0 kW/m$^2$), Victorian Ash (10.4 kW/m$^2$), and Blackbutt (9.7 kW/m$^2$) (Carlsson, 1999). Generally, the higher is the assumed value for critical heat flux for ignition of combustibles, the smaller will be the value of the suggested SSD and vice versa. Assuming a very low value of critical heat flux for ignition of combustibles, which corresponds to very large of value of SSD, poses risk for functional and economic feasibility of storage site.

**Figure 6** Outward radiative flux and SSD for MSW bale storage (see online version for colours)




There are several other simple and generalised correlations that could be employed for determining the outward radiative flux to external targets $\dot{q}''$, such as $\dot{q}'' = 20.7\,(L/D)^{-1.61}$ (Ufuah and Bailey, 2011) and $\dot{q}'' = 15.4\,(L/D)^{-1.59}$ (Shokri and Beyler, 1989) (see Figure 7). Both models are independent of *FH*, and here *L* stands for outward distance from the centre of the flame and *D* is flame diameter (i.e., the characteristic length of the fuel source). The model of Shokri and Bevler (1989) is valid only for luminous flames and for (*L*/*D*) between 0.7 to 15 (Fleury, 2010). Although these thermal radiative flux models are based on pool fires data but still are useful to develop screening level guidelines for solid waste fuels. *Firstly*, as the waste comprising of thermoplastic (e.g., polyethylene and polypropylene) and bales wrapped with low density polyethylene (LDPE) plastic sheets on combustion, melts, and flow, creating pool fires. *Secondly*, in past, several experiments involving combustion of 3D objects were also found to well represented by the correlations of pool fire based empirical models (Heskestad, 1997). Here in this study, both the models of Shokri and Beyler (1989) and Ufuah and Bailey (2011) were compared with the empirical data of gasoline and acetone fire (Ingason et al., 2010) and MSW bale fire data (Ibrahim et al., 2015). These empirical models found to predict the radiative heat flux slightly over for gasoline and acetone (Ingason et al., 2010), and provide a good fit for MSW bale fire data (Ibrahim et al., 2015). The deviation between experimental data and correlations may attributed to varying conditions under which, experiments were performed and the means through which experimental data was collected (e.g., heat flux meter, thermography, etc.). A nice fit of empirical data of bale fire in Figure 7 shows that these models can be employed for determining the SSDs for waste fuels, however, there is still need of additional bench scale experimental studies for further validation of these empirical models as currently, there is lack of empirical data regarding outward radiative heat flux associated with different fractions of solid waste fuels.

**Figure 7** Outward heat flux from a fire source as a function of *L*/*D*




## *3.2 Surface emissive power*

The SEP of flames on multiplying with view factor provides outward radiative flux from the fire sources. Several correlations for SEP were developed in past that are applicable for a wide range of fuel diameters (see Table 4).

Figure 8 is graphical representation of different empirical correlations. The Chaos (2017) correlation though seems to poorly fit the experimental data [see Figure 8(a)] but in general, more realistically captures the combustion physics [see Figure 8(b)]. Generally, SEP first increases, with increase in fuel diameter and then decreases due to attenuation of thermal radiation by outer cooler smoke layer (Spinti et al., 2008), and this phenomenon is well captured by Chaos (2017) and Shokri and Beyler (1989), and to some extent by Mudan and Croce (1988). Secondly, the correlation of Mudan and Croce (1988) overpredict the SEP of pool fires and underpredict the SEP of MSW bale fire (see

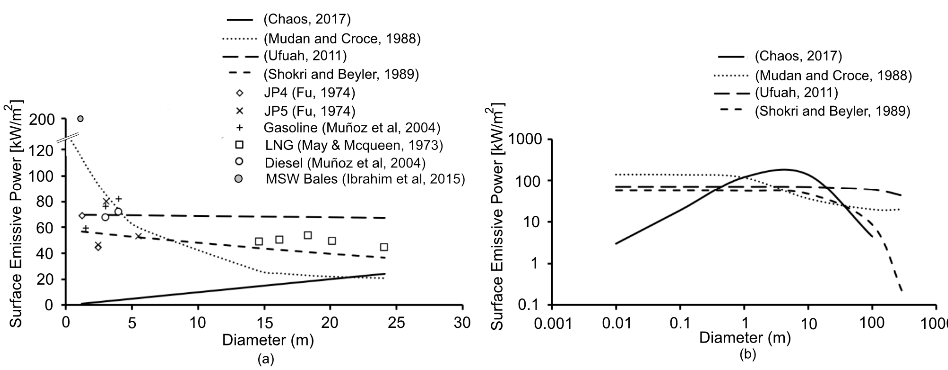
Figure 8). Considering that existing correlations are mostly developed based on pool fires, in future, additional experimental studies on 3D solid fuels e.g., forest fuels, agriculture resides, shrubs, waste and recyclables, etc. can be performed for developing the improved correlations for SEP. In a vacuum of experimental data about combustion of 3D objects, existing pool-fire-based models can be employed cautiously for establishing the screening level safety distance guidelines for waste storage sites.

**Table 4** Summary of correlations for SEP

| *Correlations* | $SEP_{max}$ $kW/m^2$ | $SEP_{smk}$ $kW/m^2$ | $k$ $m^{-1}$ | $\beta$ $m^{-1}$ | *Source* |
|---|---|---|---|---|---|
| $SEP = SEP_{\max} (e^{-kD}) (1 - e^{-\beta D}) + SEP_{smk} (1 - e^{-kD})$ | 220 | 20 | 0.049 | 0.818 | Chaos (2017) |
| $SEP = E_{\max} e^{-kD} + E_{smk} (1 - e^{-kD})$ | 140 | 20 | 0.2 | - | Mudan and Croce (1988) |
| $SEP = 70\ e^{-kD}$ | - | - | 0.00165 | - | Ufuah and Bailey (2011) |

Notes: $SEP_{\max}$ is the equivalent ideal surface emissive power attainable by fire (i.e., unobscured by smoke); $SEP_{smk}$ is the emissive power of smoke; $k$ and $\beta$ are fitting variables and $D$ is flame diameter.

**Figure 8** Empirical models and experimental data for SEP as a function of fuel diameter



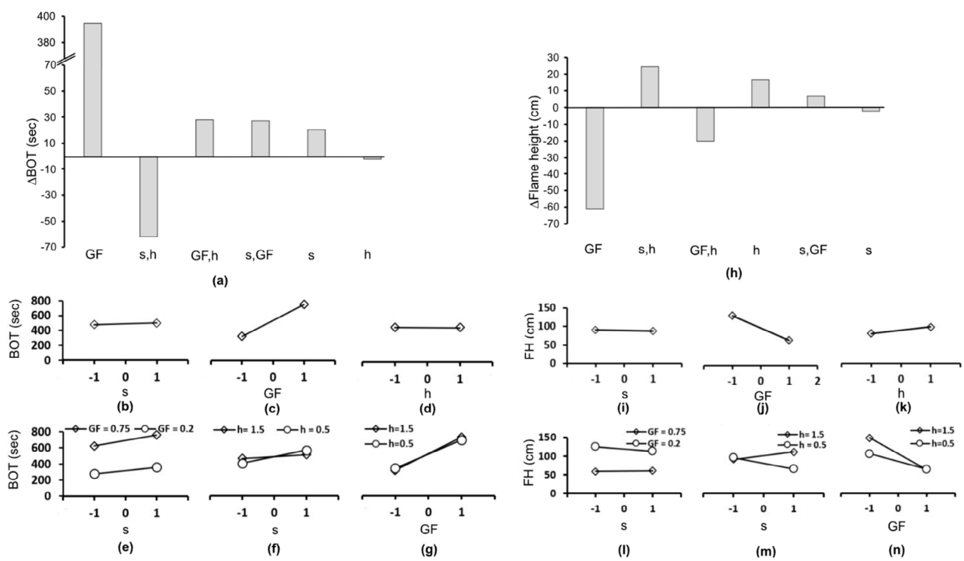

## 3.3 *Storage settings and risk of ignition of secondary fires*

The results of the main effects and the interaction effects of various storage parameters on the response variables, *FH* and *BOT* are summarised in this section and in the context of each finding, appropriate measures for minimising the risk of secondary fires are listed out.

It is found that changing the value of *GF* from 0.25 to 0.75, caused 49% (123 cm to 61 cm) reduction in '*FH*' [Figures 9(h) and 9(j)], and 132% (295 to 686 sec) increase in '*BOT*' [Figures 9(a) and 9(c)]. This shows that the parameter '*GF*' have the most profound effect on the response variables and it suggests that on having adjacent fuel units of characteristic length greater than the diameter of primary fire, the SEP of the fire source and risk for ignition of secondary fires enhances. This is important in the context that waste operators often use a combination of rectangular piles with square piles at waste storage sites [see Figure 1(c)].

Further, it is found that on changing the settings of the parameter *s* from 0.4 to 0.6 (lower level to higher level setting) caused only 2.6% change in *FH* [89.7 to 83.3 cm, see Figures 9(h)–9(i)] and 4.2% change in *BOT* [479.8 to 500.2 sec, Figures 9(a)–9(b)]. Contrarily, a change in parameter *h* from 0.5 m to 1.5 m (lower level to higher level setting), increased the *FH* by 21% [77.5 to 94.2 cm, see Figures 9(h) and 9(k)] and bring no significant change in *BOT* [<0.4%; 482.6 to 480.4 sec, see Figures 9(a) and 9(d)].

**Figure 9** Main and interaction effect of *GF*, *s* and *h* on response variables (*BOT* and *FH*)




These results of main effects of parameters *s* and *h* show that the parameter *s* has no significant effect on response variables (i.e., *BOT* and *FH*) and the parameter *h* influences mainly *FH* and has insignificant effect on *BOT*. It can be concluded that the presence of a relatively taller stockpile adjacent to the primary fire source, promotes the *FH* and thus *SEP* of primary fire source, which should be avoided to mitigate the risk of secondary fires.

The data of two-way interaction of parameters '*s* and *h*' ($I_{s,h}$) shows that on varying the value of parameter *s* from 0.4 m to 0.6 m, while keeping parameter *h* as 1.5 m (*higher-level setting*), *FH* increased by 21.3% [90 to 109 cm, see Figure 9(m)] but there was no significant change on *BOT* [increased by 9.7%, 482 to 529 sec, see Figure 9(f)]. On the other hand, on varying the value of parameter *s* from 0.4 m to 0.6 m, while keeping parameter *h* as 0.5 m (*lower-level setting*), the *FH* decreased by 31% [95 to 65 cm, see Figure 9(m)] and *BOT* increased by 41% [416 to 587 sec, see Figure 9(f)]. It is noticed that the interaction effect of parameters *s* and *h* ($I_{s,h}$) has a stronger effect on *BOT* and *FH* than that the parameters *s* and *h* has in isolation (see Figure 9). Therefore, criterion for the development of SSD should never be based on the isolated settings of the parameter *s* and *h*.

Based on these findings, it can be concluded that maintaining a large separation distance between the fire source and the adjacent structures will suppress the outward radiative flux and SEP of fire source (i.e., reduction in *FH* and increase in *BOT*) only if the height of the adjacent structures is not comparatively higher than that of the fire source. In this view, it is recommended that the height of bale stacks and waste stockpiles, organised in arrays, at waste storage sites, should be alike.

Analysis of data of phase-2 of experiments shows that changing the value of *GF* from 0.25 to 0.75 raised the *BOT* by 31.3% [506.8 to 665.8 sec, see Figures 10(a)–10(b)] and caused 39.2% (68.2 to 41.5 cm) reduction in *FH* [see Figures 10(h)–10(i)]. This shows that among the studied parameters, *GF* has the most profound effect on *BOT* and *FH*. This suggests that, in general, a larger value of *GF* (>0.5) should be maintained at waste storage sites.

Further, data shows that *BOT* increased by 27% [520 to 660 sec, Figures 10(a) and 10(d)] on changing $D^*$ from 2 to 4 but for the same level of change in $D^*$, there is no significant effect on *FH* [increased by 3.6%; 53 to 55 cm, see Figures 10(h) and 10(k)]. This shows that the spacing between fuel units ($D^*$) has a strong effect on *BOT* but has weak effect on *FH*.

Moreover, it is observed that *FH* increased by 37.8% [44.0 to 60.7 cm, see Figure 10(j)] as array size changed from 2 × 2 to 4 × 4 but for same level of change in array size, there is no significant change in *BOT* [decreased by 3.5%; 615.2 to 593.6 sec, see Figure 10(c)]. This suggest that contrarily to $D^*$, array size *N* has a strong effect on *FH* but has insignificant effect on *BOT*. This further concludes that the parameters causing increase in *BOT* not always cause reduction in *FH* and vice versa. This is particularly true for parameters $D^*$ and *N*.

Generally, for determining the SSD, more weightage should be given to such parameters that has stronger effect on *FH*. This is because, SEP and view factor, which mainly control the fraction of thermal radiations received by the target object from the fire source, are directly proportional to flame shape and size. Therefore, it is suggested that the parameter *N* is more important than $D^*$ for mitigation of risk of ignition of secondary fires. For a certain setting of $D^*$, it is always preferable to store material in the form of a smaller array than a larger array, for reducing the risk of ignition of secondary fires caused by outward thermal radiative flux from the primary fire.

The two-way interactions, ($I_{GF,N}$) and ($I_{N,D^*}$) found to have strong effect on response variables [see Figures 10(a) and 10(h)]. Data shows that setting *N* as 4 × 4 (higher level setting) and changing *GF* from 0.2 to 0.75 caused 44.6% decrease in *FH* [81.0 to 44.8 cm, see Figure 10(l)] and 20.5% increase in *BOT* [519 to 625.7, see Figure 10(e)], and on setting *N* as 2 × 2 (lower level setting), the same level of change in *GF* (0.2 to 0.75) caused 10.4% decrease in *FH* [46.5 to 41.6 cm, see Figure 10(l)] and 42% [522.7 to 742.2 sec, see Figure 10(e)] increase in *BOT*. This shows that on increasing *GF*, *FH* reduces but this effect is more profound for larger arrays. Which in other words means maintaining a certain higher value of *GF* (i.e., >0.5) would help more in reducing the outward radiative flux for a larger array than for a smaller array.

Further, in reference to interaction of $D^*$ and *N*, it is observed that on setting $D^*$ equal to 4 (*higher-level setting*) and changing array size from 2 × 2 to 4 × 4, increased the *FH* by 9.6% [53.5 to 58.5 cm, see Figure 10(n)] and increased the *BOT* by 1% [668.2 to 676.6 sec, see Figure 10(g)], and on setting $D^*$ equal to 2 (*lower-level setting*), the same level of change in *N* (2 × 2 to 4 × 4), increased the *FH* by 93.9% [34.6 to 67.1 cm, see Figure 10(n)] and caused 21.5% reduction in *BOT* [596.7 to 468.1 sec, see Figure 10(g)]. This suggests that on setting the larger values for $D^*$, increase in the array size has no significant effect on outward radiative flux [as no significant change on *FH* (9.6%) and *BOT* (1%)] but for smaller values of $D^*$, increasing the array size significantly increase the outward radiative flux (as *FH* increased by 93.9%). It is also suggested that waste operators if choose to arrange material in large arrays, $D^*$ must be enhanced to reduce the outward radiative flux.

**Figure 10** Main and interaction effect of *GF*, *D** and *N* on response variables (*GF* and *FH*)

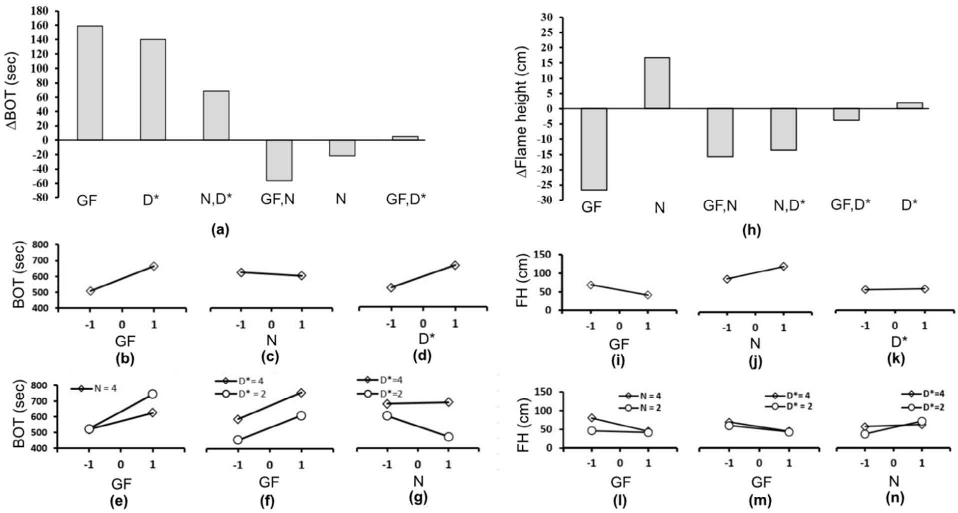
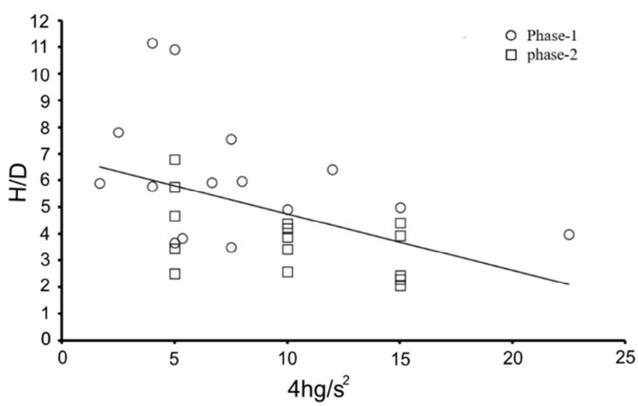



**Figure 11** Dimensionless *FH* and dimensionless storage area




The reason for not having a same order of change on *BOT* (change of 21.6%) and *FH* (change of 94%) for above mentioned conditions is the inward air entrainment towards the centre of the fire array caused by the pressure gradient and creation of a fuel rich zone at the centre of fire array. This lifts the whole combustion zone, and it takes a bit longer for air and fuel to mix and get combusted, therefore, apparently, *FH* increases, without bringing significant change in *BOT*. This is inline the with the finding of Zhang et al. (2018), in which it is deduced that the fuel rich zone at the centre of the fire array becomes more noticeable on reducing the value of $D^*$ and temperature along the centre line first decreases (due to incomplete combustion in fuel rich region), then increases to its maximum value and afterwards decreases again.

Furthermore, it is found that the dimensionless number 4 hg/s$^2$ (ratio of air flow area to storage area) is negatively related with dimensionless *FH* (*H*/*D*; ratio of *FH* to fuel diameter) (see Figure 11). Considering that the smaller the *FH*, the lower will be the value of SEP of the fire source, and less will be the risk for ignition of secondary fire caused by outward thermal radiative flux from the primary fire source, it is deduced that, in general, maintaining a large value for 4 hg/s$^2$ would improve the fire safety of the storage site.

Additional recommendations related to storage of waste fuels are as follows:

- Most commonly bale stockpiles have a footprint area of 20 m × 10 m and height of 10 m (Lönnermark et al., 2019). It is recommended that instead of storing bales in the form of a single large stockpile, which could limit the accessibility of rescue services in case of emergency, organising bales in the form arrays of smaller stockpiles (5 m × 5 m, footprint area and 5 m height), could provide more safety.
- The outward radiative flux from abreast flame increases tremendously under conditions, when the ratio of separation distance between fuel-units to linear dimension of fuel-units <1 (Shanon et al., 2020; Zhang et al., 2018; Liu et al., 2013) and such conditions should be avoided at storage sites. This suggests that in general, $D^*$ should always be greater than unity at waste storage sites.
- In view of high toxicity and difficulty in handling of fire extinguishing water, waste to energy companies prefer to cover the waste fires with soil or other inert material, instead applying water for fire extinguishment (Lönnermark et al., 2019). Therefore, besides having SSD between waste stockpiles, waste operators should always leave additional free space at storage sites to quickly separate out the material that undergo combustion from the rest of the pile and to cover it with some inert material.
- The SSD for conducting firefighting operation (principally based on accessibility to fire and safety of firefighters) at a waste site may differ from the SSD that prevents the ignition of adjacent waste stockpile (principally based on outward thermal radiative flux). According to the HSB engineering insurance company, the SSD for firefighting is 45 m and it is proposed that no portion of the stockpile should be more than 45 m from any access road (HSBEL, 2014).
- Besides the layout of the array of waste stockpiles, the overall layout of the whole waste facility also influences the site accessibility and efficiency of fire rescue operation. The overall design layout of whole waste handling facility in relation to risk of waste fire incidents is not comprehensively explored hitherto, though some recommendations related to layout of waste transfer stations and recycling stations are developed by Swedish waste management association (Avfall Sverige, 2013).
- The requirements for maintaining the SSD can be reduced or eliminated e.g., by employing low thermal conductivity partition blocks with insulating properties (Leiva et al., 2013; Yan et al., 2018) between waste stockpiles. Furthermore, considering that in the past, use of broad leaves deciduous vegetation along the roads found useful as fire barrier against spread of wildfires (Molina et al., 2019), the use of deciduous vegetation between waste stockpiles and around the waste storage site could help in reducing the risk of ignition of secondary fires at waste storage sites.

## 4 Conclusions

It is concluded that the outward thermal radiative flux from the primary fire source, using isotropic thermal radiation model, is a suitable criterion for the development of SSD. The contour plots of SSD presented in the article can be employed for safely stockpiling the waste bales and the correlations of Ufuah and Bailey (2011) and of Shokri and Beyler (1989) can be employed for predicting the outward radiative flux for MSW bale fires. It is concluded that the main effect of parameters *GF* and $D^*$, and interaction effects of the parameters *s* and *h* ($I_{s,h}$), *GF* and *N* ($I_{GF,N}$) and *N* and $D^*$ ($I_{N,D^*}$) have strong effect on the response variables (*BOT* and *FH*). It is observed that parameters effecting the *FH* not necessarily bring the same order of change in *BOT*. On comparing parameters *s* and *h*, *FH* is found to be more sensitive to the setting level of *h* and less sensitive to the setting level of *s*. Similarly, on comparing parameters *N* and $D^*$, *FH* is found to be more sensitive to the setting level of *N* and less sensitive to the setting level of $D^*$. Further, *FH* is found to be more sensitive to the size of array, while having smaller value of $D^*$ than while having larger values of $D^*$. The parameter *BOT* is more sensitive to the setting level of $D^*$ and less sensitive to the setting level of *N*. In certain cases, interaction effects found to have more profound effect on response variables than that of isolated main effect of individual parameters, e.g., two-way interaction of $s – h$ has even more profound effect on *FH* than the isolated effects of parameters *s* and *h*. Therefore, the criterion for the development of SSD should never be based on isolated settings of the parameters *s* and *h* alone. It is suggested that on switching from smaller array to a large array size, $D^*$ must be enhanced to subside the outward radiative flux from the fire array. Moreover, the characteristic length and height of the adjacent fuel units should not be greater than the characteristic length and height of the primary fire source. The effect plots and the contour plots presented in the article can be employed as a basis for the development of screening level guidelines for MSW bale storage sites. In future, research is needed to study interaction of fire sources having non-identical power and to quantitatively investigate the phenomenon of air entrainment during group fires.

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## Notes

1 $\left[\left(800\Big/\left(\frac{\pi d^2}{4}+\pi dl\right)\right)\right]$ (bale diameter 1 m and bale height 1 m).