Vol. 9(9), pp.104-114, December 2018
DOI: 10.5897/JSPPR2018.0268
Article Number: 687640559623
ISSN: 2141-6567

http://www.academicjournals.org/JSPPR

ACADEMIC JOURNALS
expand your knowledge

Journal of Stored Products and Postharvest Research

Full Length Research Paper

Selection, characterization and identification of smokes from different biomass materials as a medium for modifying the atmosphere for stored grain

Yetenayet B. Tola[1*], Obsuman D. Muleta[1] and Werner C. Hofacker[2]

[1]Department of Postharvest Management, College of Agriculture and Veterinary Medicine, Jimma University, P. O. Box 307, Ethiopia.
[2]Institute of Applied Thermo and Fluid Dynamics, Konstanz University of Applied Sciences, D-78462 Konstanz, Germany.

Received 18 August, 2018; Accepted 8 November, 2018

In developing countries, losses of stored grains due to insect pests are significant. Modified atmosphere (MA) storage is one of the strategies to minimize impact of the pests. This work aimed to identify a biomass material for generating smoke having high concentrations of CO and CO_2 to create a MA in stored grains. Smokes from seven biomass were characterized in terms of CO, CO_2, NO and O_2 composition. Results showed that smoke from dried maize stalk (MS) was superior in terms of generation of high concentrations of CO (>2% vol) and CO_2 (>11% vol) with relatively less NO (< 70 ppm vol) but high rate of O_2 (< 11% per volume) depletion. MS is also easily available in farms with no cost; its smoke imparts less smell and flavor on grains and critically avoids deforestation unlike use of other biomasses. Therefore, it could serve as a medium for modifying stored grain atmosphere through accumulation of high concentration CO and CO_2. Furthermore, during infusion, it expels ambient air from interstellar space of grains to modify storage environment. An efficient smoke infusion device and hermetic storage structure are required to benefit from created MA against grain insect pests.

Key words: Carbon dioxide, carbon monoxide, modified atmosphere, smoke, storage pest.

INTRODUCTION

One of the critical challenges in developing countries is to ensure food and nutrition security whilst ensuring long-term sustainable development. This is mainly because of change in climate, high rate of population growth, low productivity of agriculture and high postharvest loss of harvested crops.

According to Zorya et al. (2011), sub-Sahara African (SSA) countries significantly experience about 4 billion USD loss each year due to poor after harvest handling of grains mainly during storage. In SSA countries, grains are stored in traditional storage structures made up of different local materials. Due to limitations of the structures, grains loss due to insect pest is significant. Costa (2014) estimated a 59.5% loss of maize after 3

*Corresponding author. Email: yetenayet@gmail.com, yetenayet.bekele@ju.edu.et.

Figure 1. Biomass materials identified during FGD and KII to use as a potential smoke source materials.

months of storage, and on average, 64.5% damage was reported within three to six months of storage in South-West part of Ethiopia (Sori and Ayana, 2012). Storage related loss of wheat in Bangladesh was estimated at 41.7% of total harvest (Bala et al., 2010), whereas in Guatemala, it was 45% of total stored maize (IAICA, 2013).

Farmers commonly use different types of preventive and curative insecticides to control impacts of insect pests' damages on stored grains. However, in developed nations, agricultural products can be stored under modified (MA) or controlled atmosphere (CA) environment to control stored grain pests without use of insecticides. As reported in Donahaye and Navarro (2000), MA/CA is a non-toxic and environmentally sound storage technology to control impact of pests in stored products.

Infusion of CO_2 from pressurized cylinder, on site generation and infusion of nitrogen gas, use of ozone and combustible gases are major active modification methods. In passive modification process, living organisms (aerobic fungi, insects and grains) in air tight storage structure consume O_2 and are reduced to lower level while building up CO_2 (White and Jayas, 1991). Such a modified environment kills insect pests, mites and limit proliferation and impact of aerobic fungi (Weinberg et al., 2008). Modern active modification methods are feasible for large-scale commercial farms and volume of grains. However, the principle can be equally applicable at small-scale level as long as low cost alternative approaches are available. Combustible gases from gas burners are one of onsite modification of MA through burning of hydrocarbon fuel. Combustion of propane and butane yields approximately 13 and 15% CO_2, respectively (Navarro et al., 1995). However, creation of high concentration of CO_2 and CO environment is feasible through burning and infusion of locally available biomass materials in hermetic storage structures.

Generated smoke from combustion process can serve as means to get rid of ambient air from interstellar space of stored grains. Under hermetic condition, residual oxygen in the smoke and interstellar space is gradually depleted through passive process. With recent development and availability of flexible plastic materials like Polyvinyl chloride (PVC), different size hermetic storage structures can be constructed and combined with infusion of smoke to create a MA (Navarro, 2010). Therefore, this study aimed to characterize and identify locally available biomass materials as economical smoke source to generate relatively high concentrations of CO and CO_2 to create a MA environment in stored grain.

MATERIALS AND METHODS

Description of the study area

This survey study was conducted in three districts (Omo Nada, Keressa and Seka Chekoressa) of Jimma Zone, South West part of Ethiopia to identify potential smoke source materials. Geographically Omo Nada (07° 17' - 07°38' N latitude and 37° 00 - 37° 28' E longitude), Keressa (07° 5' - 08° 00' N latitude and 36° 46' - 37° 14' E longitude) and Seka Chekoressa (07° 20' - 7° 45 ' N latitude and 36° 29' - 36° 50' E longitude) districts are located on an altitude of 1500-2500, 1500-2660 and 1580-2560 m.a.s.l respectively. The annual average rainfall in Omo Nada, Keressa and Seka Chekorsa are 1880, 1500 and 1400 mm with average annual temperature of 16 - 27°C, 16 - 26°C and 18 - 28°C respectively.

Exploration and identification of smoke source materials

Focus group discussion (FGD) with farmers and key informant interview (KII) was used in selecting potential smoke source materials. Using pre-tested checklist, discussions were made with selected village (3 per district) farmers (4 male and 4 female) and key informants (2 male and 3 female). Recommended smoke sources were from any biomass material that could be used by farmers as energy source (e.g. woods, leaves, straw and cow dung) to cook foods or be used for other purposes. Availability of source materials in local area, cost and other cultural and religious issues were also considered during the discussions.

Preparation of smoke source materials

Identified smoke source materials chopped to small size (5-6 cm) were bulked, homogenized and sundried for 5 days. Moisture content was determined using oven (Leicester, LE67 5FT, England) drying method at 70°C for 72 h. Figure 1 shows identified and selected smoke source materials used. Bulk density of samples was also determined using gravimetric method.

Evaluation of smoke sources for additional properties

After selection of potential smoke source materials for their gases composition, further observation study was conducted in terms of temperature rise during burning, rate of burning, smell of smoke, availability of biomass in the locality, cost of biomass, and effect on forest. Evaluation was subjectively rated in four scale of zero = no effect, + = low effect, ++ = medium effect and +++= high effect.

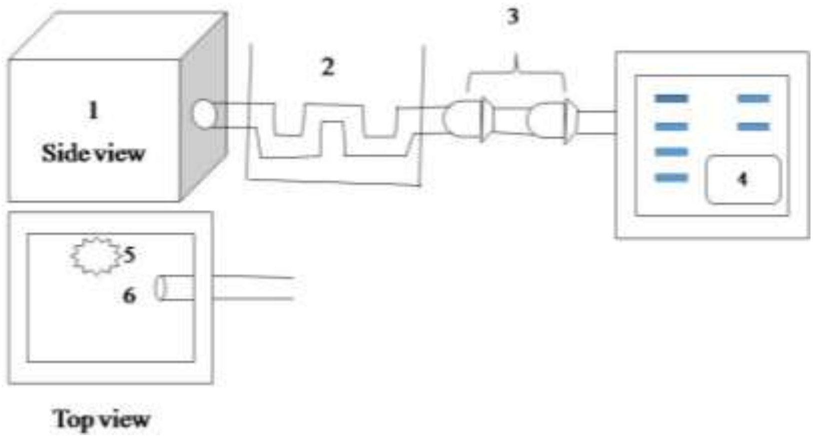

Figure 2. Experimental setup to measure gases compositions of smokes from different sources, 1= Air light sample burning stainless steel box, 2= Heat exchanger to cool smoke, 3= Filters to avoid migration of moisture and soot to gas analyzer 4= Gases measuring unit, 5= Sample burning heat source, 6= Small fan to homogenization smoke.

Table 1. Moisture content and bulk density of smoke source materials before subjected to burning.

Sample	Moisture content (%)	Bulk density (kg/m^3)
ML	4.2±0.7*	523.7±12.1
CD	6.2±0.1	662.0±16.8
MS	6.5±1.2	670.0±30.0
MC	6.2±0.01	674.7±23.1
OAB	5.8±1.1	689.30±6.0
FUCH	4.2±0.5	718.8±16.0
OAW	7.0±0.3	770.3±25.1

Note:*mean ± standard error values; ML=*Maesa lanceolata,* CD=Cow dung, OAB=*Olia Africana* bark, OAW=*Olea africana* wood, MC=Maize cob, MS=Maize stalk, FUCH=fully not burnt charcoal.

Experimental set up to characterize smoke source materials

A laboratory study was conducted to characterize smokes from source materials in terms of CO_2, CO, NO (Nitrogen Oxide) composition and O_2 depletion rate during burning in enclosed metal box. Change in gases (CO_2, CO, NO, O_2) concentrations in smoke was recorded in regular time interval. For characterization purpose, sample burning box was constructed using stainless steel metal having a total volume of 0.125 m^3 (0.5 m x 0.5 m x 0.5 m) and net void volume of 0.119 m^3. Small metal box (0.10 m x 0.05 m x 0.05 m) for burning samples using electric oven (1500 W) served as heat source maintaining heating level at medium capacity. Characterization of smoke was conducted in two subsequent steps using 20 and 40 g samples for screening and verification steps respectively. Smoke uniformly mixed in burning chamber (Figure 2) with small fan and cooled in rubber tube immersed in cold water (10-15^{o}C) before it passes through two smoke filters. Eventually sucked smoke was characterized in terms of composition of CO (% volume), CO_2 (% volume), O_2 (% volume) and NO (ppm volume) using gas analyzer (Saxon Junkalor, INFRALYEL, Germany). Figure 2 shows the experimental set up of sample burning and measurement units to characterize smokes in terms of the gases composition.

Experimental design and data analysis

One factor factorial experiment in complete randomized design (CRD) was used to characterize homogenized smokes in enclosed metal box. Samples measurements was replicated three times and mean values presented with standard error of mean. Data analysis was conducted with one-way analysis of variance (ANOVA) using Minitab computer statistical software program (version 16) and Tukeys' studentized range test (HSD) at 5% level of significance to separate means when smoke sources in their gases composition were found significant.

RESULTS AND DISCUSSION

Variation in moisture content and bulk density of samples

Table 1 shows moisture content and bulk density of smoke source materials before burning. Based upon nature of the materials, moisture content varies from 4.2 to 7%. ML and FUCH had the lowest moisture content of

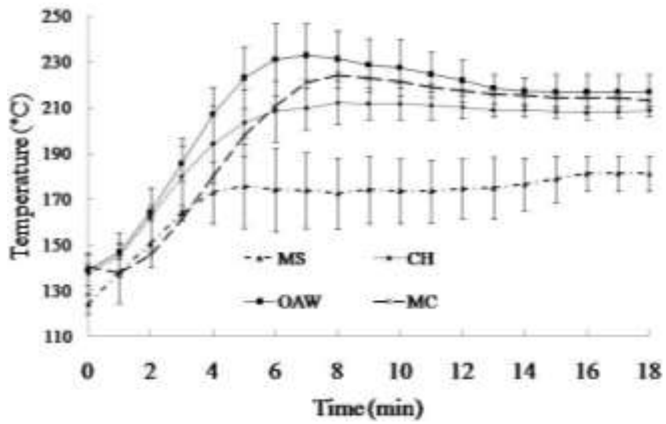

Figure 3. Rate of temperature increase during burning of selected biomass materials (this parameter is determined only for selected four biomass materials).

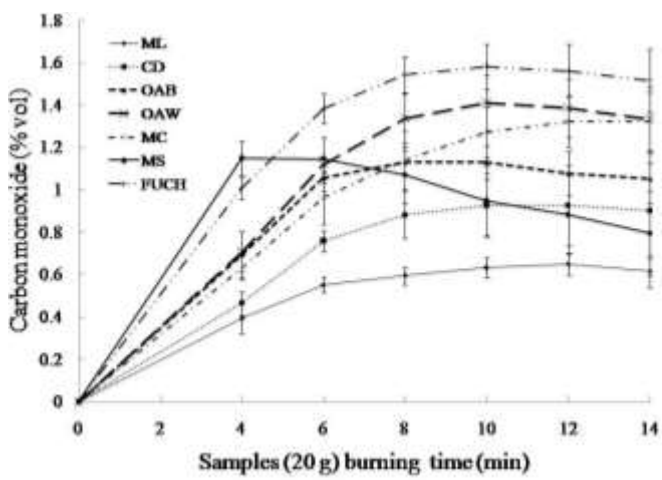

Figure 4. Carbon monoxide formation and accumulation from different smoke source materials for 20 g samples (ML= *Maesa lanceolata* OAB= *Olia Africana* bark, MC= Maize cob, CD=Cow dung, OAW= *Olea africana* wood, MS= Maize stalk and FUCH = fully not burnt charcoal.

4.2%, followed by OAB, CD, MC, MS and OAW. As indicated in Figure 3 for selected biomasses (MS, MC, OAW and FUCH) of 40 g samples, biomass with lower bulk density (MS) exhibited faster rate of burning with lowest temperature rise (Figure 3) regardless of moisture content of the biomasses.

Combustion of biomasses occurred through three different but subsequent stages of drying, devolatalization and char burning. Drying phase correlated with migration of moisture as the higher the moisture the lower the rate. However, as reported in Orang and Tran (2015), only biomass samples having more than 30% showed a significant effect on rate of burning with insignificant effect on devolatalization and char burning. Shen et al. (2013) reported a strong positive correlation of emission factors with moisture content of wood during combustion. However, in this study, due to less difference (< 3%) in moisture content, a significant difference in emission factors may not be expected. Due to less moisture content and variation in chemical composition of biomass samples in this study, the bulk density could determine rate of burning and temperature rise than moisture content.

Variation in CO production and accumulation

In the study, smokes from different biomass materials showed significant ($p<0.05$) difference in terms of generation of CO. As indicated in Figure 4, for 20 g

Table 2. Formation, accumulation and depletion of different gases from burning of biomass materials with time for sample size of 40 g.

Smoke sources	4 min	6 min	8 min	10 min	12 min	14 min	16 min	18 min
CO formation and accumulation (% per vol)								
MS	1.29±0.1[a]	1.89±0.09[a]	2.10±0.06[a]	2.17±0.05[a]	2.20±0.04[ab]	2.18±0.05[b]	2.16±0.05[b]	2.13±0.07[b]
MC	0.67±0.05[b]	1.24±0.06[b]	1.71±0.06[b]	1.92±0.06[b]	2.02±0.07[b]	2.08±0.08[b]	2.10±0.1[b]	2.12±0.11[b]
OAW	0.57±0.05[b]	1.36±0.13[b]	1.87±0.1[ab]	2.19±0.08[a]	2.36±0.04[a]	2.44±0.08[a]	2.48±0.1[a]	2.48±0.11[a]
FUCH	0.72±0.06[b]	1.28±0.09[b]	1.80±0.1[ab]	1.99±0.1[ab]	2.11±0.05[b]	2.20±0.05[ab]	2.24±0.05[ab]	2.21±0.02[ab]
CO_2 formation and accumulation (% per vol)								
MS	4.1±0.3[a]	6.4±0.3[a]	7.9±0.4[a]	8.8±0.4[a]	9.6±0.3[a]	10.2±0.2[a]	10.6±0.2[a]	10.9±0.20[a]
MC	2.2±0.1[b]	3.9±0.2[c]	5.5±0.1[b]	6.8±0.1[b]	7.6±0.2[c]	8.5±0.2[b]	9.0±0.2[b]	9.4±0.2[bc]
OAW	2.0±0.2[b]	4.1±0.2[c]	5.6±0.3[b]	6.5±0.4[b]	7.5±0.4[c]	8.1±0.4[b]	8.5±0.4[b]	8.9±0.4[c]
FUCH	2.8±0.3[b]	5.1±0.2[b]	7.1±0.4[a]	7.8±0.5[ab]	9.1±0.3[a]	9.8±0.3[a]	10.2±0.4[a]	10.5±0.4[ab]
Consumption of oxygen (% per vol)								
MS	18.8±0.5[a]	15.2±0.4[a]	13.2±0.4[a]	12.1±0.4[a]	11.1±0.3[a]	10.4±0.2[a]	10.0±0.2[a]	9.6±0.02[b]
MC	19.7±0.1[b]	18.0±0.1[b]	16.2±0.2[b]	14.1±0.3[b]	13.1±0.1[b]	12.2±0.1[b]	11.5±0.2[b]	11.0±0.04[c]
OAW	19.6±0.1[b]	17.6±0.3[b]	15.5±0.3[b]	14.1±0.3[b]	12.7±0.2[b]	11.9±0.2[b]	11.1±0.2[b]	10.6±0.07[c]
FUCH	18.2±0.4[a]	15.7±0.7[a]	13.5±0.7[a]	11.7±0.5[a]	10.5±0.4[a]	9.7±0.4[a]	9.2±0.4[a]	8.6±0.3[a]
NO formation and accumulation (ppm per vol)								
MS	51.8±9.9[a]	67.3±10.5[b]	72.3±6.0[c]	70.5±4.0[b]	67.3±3.4[b]	63.5±2.3[b]	60±2[c]	57±1.2[c]
MC	35.5±2.4[b]	71±5.9[a]	90±4.2[b]	92.8±3.2[a]	88.8±2.6[a]	84±2.5[a]	79±2.3[a]	74±2.5[a]
OAW	29.3±2.1[c]	68±2.2[b]	94±3.9[a]	92±3.6[a]	85.5±3.3[a]	82.3±5.4[a]	74±3.9[b]	69±4.9[b]
FUCH	33.8±4.5[b]	52.3±3.6[c]	59.8±2.2[d]	60.5±1.8[c]	56.8±1.8[c]	52.3±1.9[c]	48.5±1.8[d]	43.3±1.8[d]

Note:* mean ± standard error values; ML=*Maesa lanceolata,* CD=Cow dung, OAB=*Olia Africana* bark*,* OAW=*Olea africana* wood*,* MC=Maize cob, MS=Maize stalk, FUCH=fully not burnt charcoal.

samples, MS, CD and ML results in lower CO generation and accumulation as compared to biomasses having relatively higher bulk density (FUCH, OAW and MC). Even though MS showed faster rate of generation of CO for the first 6 min, with burning of the sample, a faster decline in concentration was observed. However, production and accumulation of CO for OAW and FUCH increased with an increase in burning time. After 6 min of burning, more than 1% (per volume) CO concentration was recorded for most of the biomasses except ML, CD and MS.

In subsequent work, a verification study was conducted by increasing samples size to 40 g for four selected samples (MS, MC, OAW and FUCH). MS was included in the list due to its fast CO generation capacity. It was observed that there was more than 1.5% (per volume) CO concentration after 8 min of burning (Table 2). However, unlike in 20 g sample, MS smoke for 40 g sample results in more than 2% (per volume) concentration of CO after the same sample burning time. Figure 5 presents percent increase in CO concentration by doubling samples mass. The highest percent increase is for MS (more than 50% increase after 10 min of burning), followed by OAW (>30%), MC and FUCH (>20%). This gives an opportunity to increase CO concentration and accumulation through increasing of sample size for better modification of storage environment against insect pests.

Jayas and Jeyamkondan (2002) indicated that modification of stored grain environment using modified atmosphere, involves the alteration of the natural storage gases such as CO_2, O_2 and N_2 to render the atmosphere in the stores lethal to insect pests. In addition to these gases, CO can modify gases composition and a relatively high CO percentage is poison to human and other creatures under enclosed and less ventilated condition.

When lethal concentration of CO is considered, exposure to 4.000 ppm (0.4% per volume) concentration for 30 min could cause an immediate death to human being (Lefaux, 1968). According to the National Institute for Occupational Safety and Health, USA (NIOSH) (2018), of the immediately dangerous to Life or Health (IDLH) concentration is 1200 ppm (0.012% per volume). However, smokes from MS, OAW and FUCH consisted of more than 100 times concentration under an enclosed condition. If this high concentration is strictly controlled

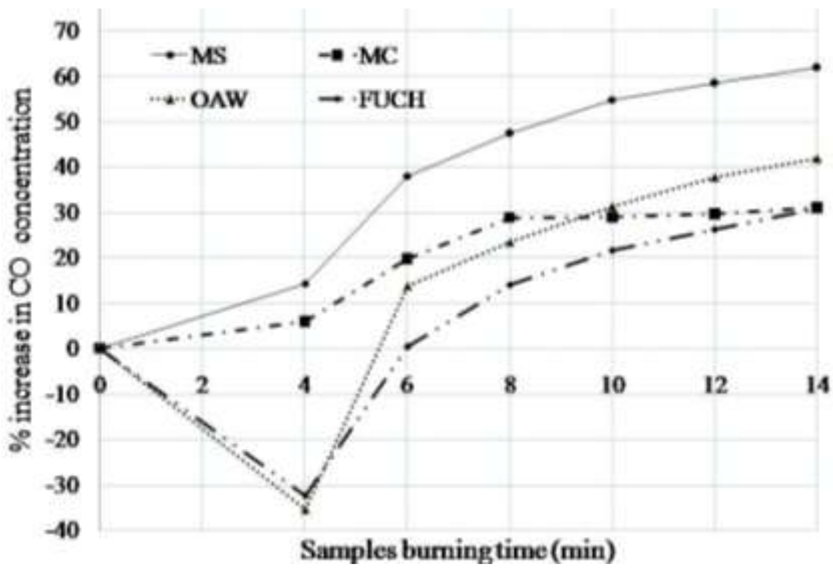

Figure 5. Percent increase in formation and accumulation of CO when smoke samples size increased from 20 to 40 g.

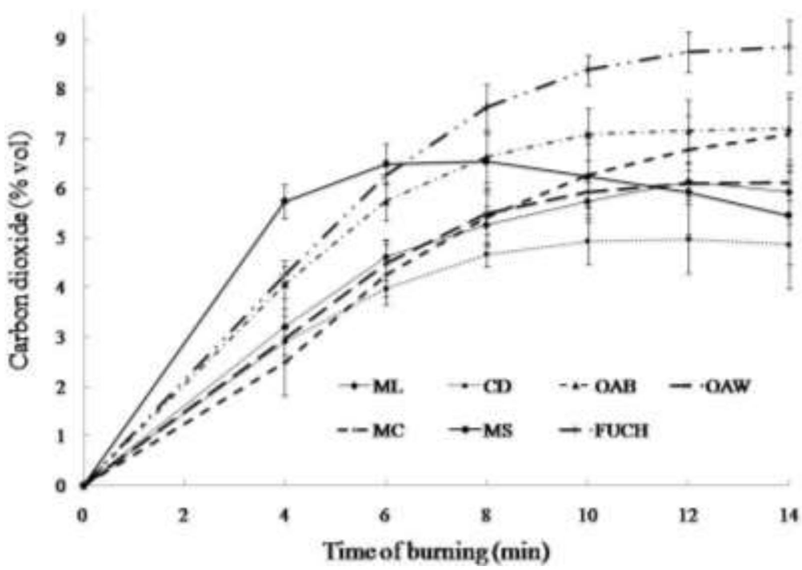

Figure 6. Carbon dioxide formation and accumulation from different smoke source materials with materials burning time (20 g sample size).

and properly infused in stored grain, it will critically help to control impact of stored grain insect pests. However, it is hoped that literature data in this regard be compared with this study results.

Variation in CO_2 production and accumulation

Figure 6 shows increase in formation and accumulation of CO_2 during burning of different biomasses (20 g sample size). MS showed fast burning and CO_2 formation for the first 6 min and declined with time. ML and CD show low level of CO_2 production and accumulation when compared with other samples. This might be associated with low bulk density of the three samples (MS, ML and CD) as compared to others (Table 1). OAW, OAB, MC and FUCH exhibited slow rate of burning as compared to samples that exhibited a continuous accumulation of smoke and CO_2 with time (Figure 6).

Increase in CO_2 concentration with an increase in

Table 3. Additional observed properties (in relative term with other) during burning of four selected biomass materials as smoke source materials.

Smoke source	Relative comparison values of additional observed properties				
	Rate of burning	Smoke smell	Availability	Cost	Effect on forest
MS	+++	+	+++	+	0
MC	++	+	++	++	0
OAW	+	+	+	+++	+++
FUCH	+	+	++	++	+++

Note: ML=*Maesa lanceolata,* CD=Cow dung, OAB=*Olia Africana* bark*,* OAW=*Olea africana* wood*,* MC=Maize cob, MS=Maize stalk, FUCH=fully not burnt charcoal.

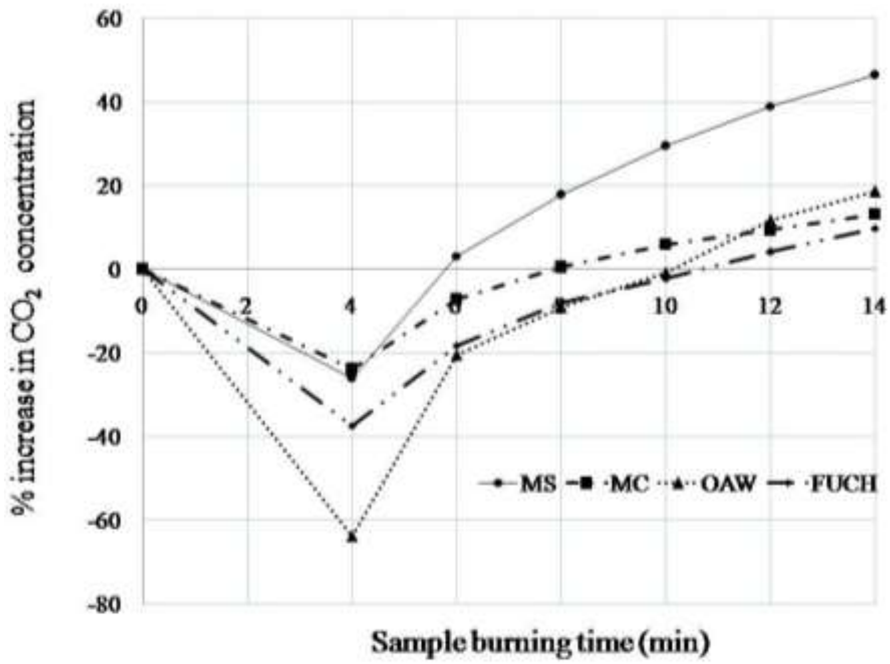

Figure 7. Percent increase in formation and accumulation of CO_2 when smoke samples size increased from 20 to 40 g.

sample size showed significant effect ($p<0.05$) as indicated in Table 2. MS and FUCH showed fast and constant increase in CO_2 production and accumulation with samples burning time. As indicated in Table 2, the concentration reached more than 10% at the end of burning time for 40 g sample (Table 3). OAW and MC showed inferior results as compared to other two sources. There could be a synergetic lethal effect on storage insect pests due to combined action of high concentration of CO and CO_2 in a given MA environment. Feng et al. (2009) reported on the combined effect of CO and CO_2 on higher mortality of insect pests.

Increase in CO_2 concentration as well as in sample size might be associated with production of more volume of smoke with fast depletion of O_2 in an enclosed system. Likewise, regarding CO, it is understood that with an increase in sample size there is an opportunity to produce a MA having 10% CO_2 concentration using MS smoke.

Figure 7 shows percent increase gained in CO_2 concentration due to doubling of sample mass. After 12 min of burning, more than 40% increase in CO_2 concentration could be achieved when MS is used as a source. However, for other samples (MC, OAW and FUCH), doubling samples size contributed only less than 20% increase in CO_2 accumulation.

Carbon dioxide is one of the gases commonly used to modify grain storage atmosphere. As a method for insect control in bulk commodities, MA systems increase CO_2 or decrease O_2 atmospheres, or a combination of both was used (Donahaye and Navarro, 2000). In modern MA conditions, the gases composition in storage structures is

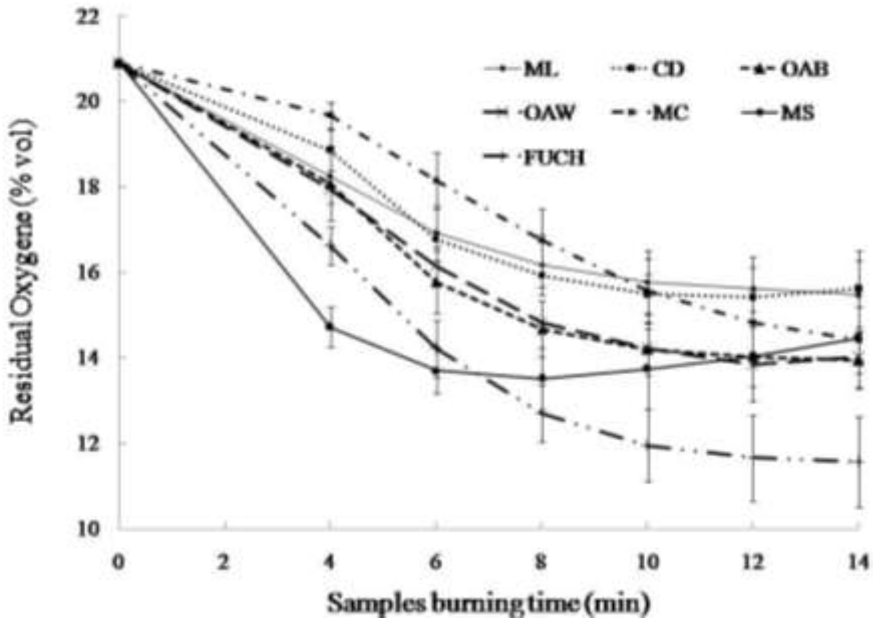

Figure 8. Oxygen depletion during burning of different smoke source materials for 20 g samples.

modified through injection of CO_2 gas (active modification) with the balance of air. However, application of the same method in developing countries is not feasible and accessible. As an alternative method for traditional small or medium grain storage hermetic structures, smoke from different biomasses can be used as a means to generate relatively high concentration CO_2 and CO.

Increase in CO_2 concentration with an increase in sample size might be associated with production of more volume of smoke with fast depletion of O_2 in an enclosed system. Similarly, for CO, it is understood that with an increase in sample size there is an opportunity to produce a MA having 10% CO_2 concentration using MS smoke as a medium to inject CO_2. There may be a synergetic lethal effect on storage insect pests due to combined action of high concentration of CO and CO_2 in a given MA environment.

Study indicates that grain MA above 10% CO_2 concentration assists spiracles of insect pests permanently open and results in insects death from dehydration, enhance CO_2 toxicity through tracheae, acidification of hemolymph of insects leading to membrane damage and death of insects (Nicolas and Sillans, 1989). Elevated but sublethal CO_2 levels for prolonged periods can have deleterious effects on insect development, growth and reproduction (White and Jayas, 2003; Nicolas and Sillans, 1989). In higher temperature areas (associated with high ambient temperature of low land areas in Africa), even low levels of CO_2 (7.5 - 19.2%) for prolonged periods sharply increase adult insects mortality (White et al., 1995).

Variation in O_2 consumption and depletion during samples burning

As indicated in Figure 8, MS and FUCH show fast depletion of oxygen (under enclosed system in sample burning chamber) for the first 6 min; but when burning time-increased, concentration of O_2 slightly increased for MS. However, burning of other biomass materials resulted in a consistent decline in O_2 concentration and the highest depletion is for FUCH sample (Figure 8).

Even though FUCH showed a better O_2 depletion during burning of 20 g sample, MS of 40 g exhibited equivalent performance like CH. As indicated in Table 2, percent residual oxygen left after 18 min of burning were less than 10% for MS and FUCH. Therefore, apart from its potential to produce relatively high concentration of CO and CO_2, MS is also enabled to minimize residual O_2.

Figure 9 shows percent decrease in O_2 concentration in a smoke burning of 40 g selected biomasses. The study showed that it is possible to achieve more than 30% decrease in O_2 concentration for MS after 12 min of burning for 40 g sample.

The availability of sufficient amount of oxygen in stored grain is a critical factor in terms of supporting the survival and reproduction of insect pests. Depletion in O_2 concentration with simultaneous accumulation of CO and CO_2 from a smoke source and removal of ambient air from stored grain can modify gases composition and influence reproduction and survival of insect pests negatively. With time, grains, moulds and insects will consume the residual O_2 in hermetic storage structure with production of more CO_2 passive process to create

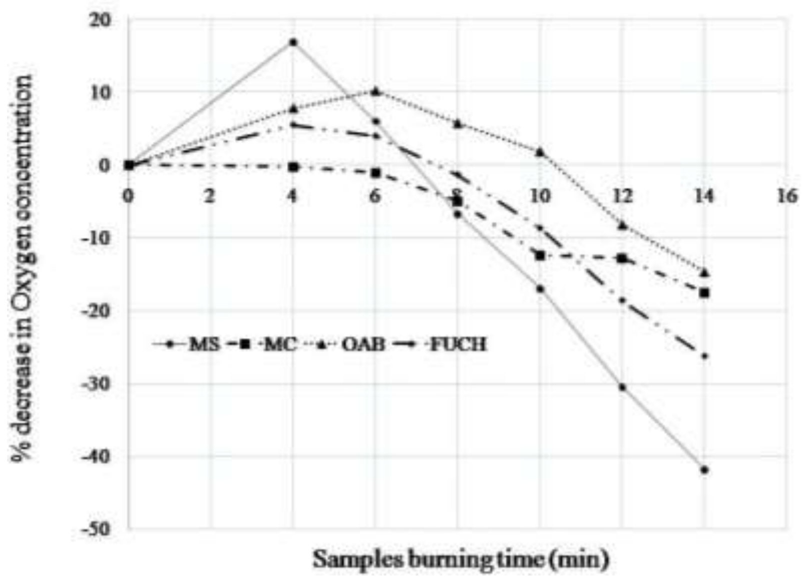

Figure 9. Percent decrease in O_2 concentration during burning when samples size increased from 20 to 40 g.

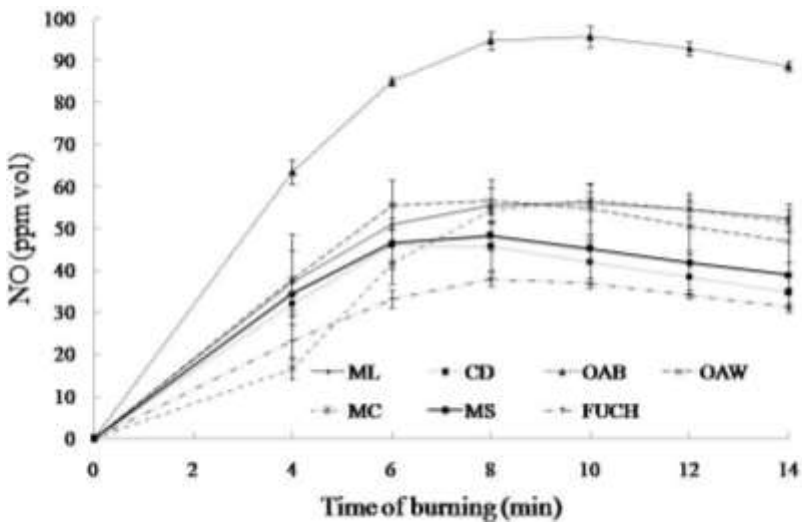

Figure 10. Formation and accumulation of NO during burning of different smoke source materials (20 g sample size).

hostile atmosphere to the pests (Moreno-Martinez et al., 2000). The combined effect of high CO and CO_2 concentrations together with low O_2 percentage at the beginning of hermetic storage could enhance mortality of storage insect pest (Annis and Morton, 1997) and minimize or avoid storage related losses of grains.

Formation and accumulation of nitric oxide (NO)

Results in Figure 10 indicate that smoke from OAB contributed to accumulation of high concentration of NO as compared to other smoke sources. This might be associated with relative high presence of nitrogen containing compounds like protein in the bark than other sources. The lowest concentrations were from CD and FUCH, which might be due to loss of nitrogen emanating from fermentation of CD and burning of wood during charcoal making. MS demonstrated more or less reduced level of NO like other biomasses with less impact on the environment unlike that of OAB (Figures 10 and 11, Table 2).

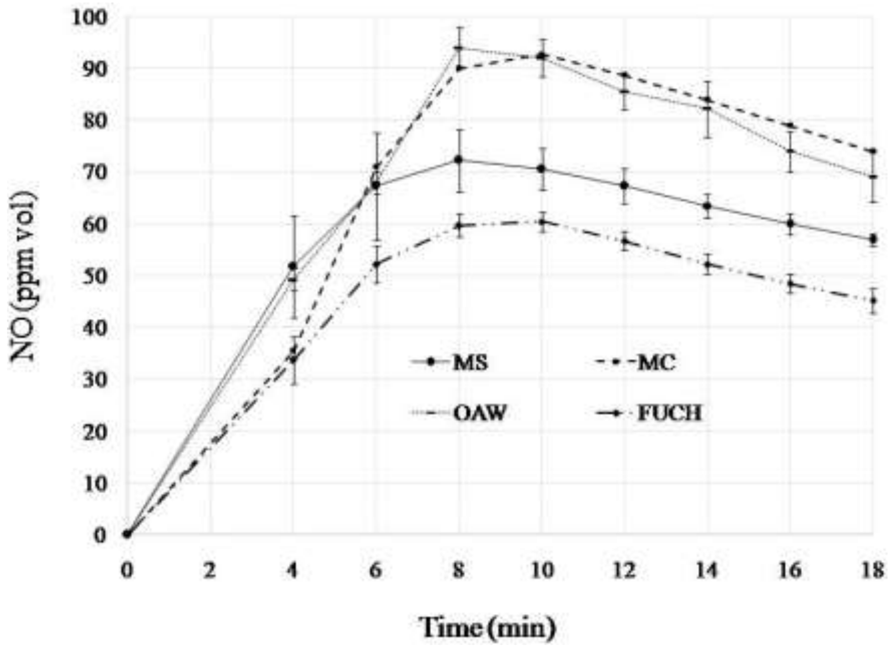

Figure 11. Percent increase in NO concentration during burning of samples when samples size increased from 20 to 40 g.

In combustion system, NO is formed in presence of high concentration of nitrogen and oxygen at high temperature. Emission of oxides of nitrogen (NOx) in the air is primarily in the form of NO, and once formed; NO oxidized rapidly to NO_2 in the presence of ozone (US EPA, 2018). These two forms of NOx (nitrogen mono (NO) and dioxides (NO_2) are the two major pollutants of air (World Bank Group, 1998).

From insect pests control point of view, NO plays diverse physiological processes like reproduction, locomotion, learning and memory (Müller, 1997; Davies, 2000). It is also used as a potent fumigant against various life stages of insect pests (Liu, 2013). However, due to its high reactive nature with oxygen, it forms NO_2, and hence such benefits achieved under ultra low oxygen concentration, which is very unlikely to get NO benefits under this study conditions. As indicated in Table 2, by doubling sample size (40 g), accumulation of NO increased as expected. MC and OAW showed significant increase as compared to MS and OAW.

Additional properties of biomass materials

Table 3 shows ranked values of additional observed characteristics of smokes and smoke source materials. MS selected as a biomass contribute to fast rate of burning (+++), smoke with less smell (+), wide availability in the farm (+++), no or low cost for purchase and preparation (+) as well as it has no effect on deforestation (0) unlike that of OAW and FUCH.

Rate of burning of biomass is an important factor for quickly generating smoke to be infused in storage structures. It was observed that MS had fast rate (+++) of burning as compared to other sources. Smoke smell is another factor which may be associated with alternation of sensorial properties of grains. Smoke with bad smell could impart undesirable taste, aroma and flavor to gain flour. In this regard, smokes from all four selected materials resulted in less smell as compared to smokes from CD and ML (data not indicated in Table 2). Availability and cost are the two major factors for small-scale farmers to use smoke sources in creating MA. In this regard, MS is easily available and abundant after harvest with no additional cost to use. Commonly, the stalk functions as a source of fuel to cook family food on a daily basis. In addition to this, the use of MS as smoke source material imposes no effect on deforestation unlike that of *Olia africana* wood and charcoal.

Conclusion

Food and nutrition insecurity is apparent in most of sub Sahara Africa counties due to low productivity and climate impacts. High after harvest losses of crops further aggravate existing gaps in the countries. Among multiple postharvest loss causes, losses imposed due to storage insect pests is significant. This coupled with traditional storage structures and lack of improved insect pest control methods. Recent storage technologies associated with hermitic storage structures are also either expensive or are not suitable for storing crops like maize with cob and sorghum head in study zone. Use of modern CA or MA storage structures with infusion of CO_2 gases from commercial sources is not available, feasible and compatible with traditional storage structures and methods. However, use of smoke having high concentration CO and CO_2 could enable modification of gases composition in stored grain environment. In addition to this, infused smoke could enable expulsion of ambient air at high O_2 percentage. In this study, chopped and dried maize stalk identified as a good source of CO and CO_2 for small-scale farmers with sufficient availability, attracts no cost and impact on forest. Infusion of the smoke enables accumulation of high concentrations of CO and CO_2 with low O_2 percentage. Under hermitic condition, actively modified environment gets further support by passive modification with depletion of O_2 and accumulation of more and more CO_2 to hinder activity and reproduction of insect pests. As additional recommendation, the inner layer of traditional storage structures are better lined with air proof locally available plastic (polyvinyl chloride) to create hermetic and maintain MA environment. Creation of efficient MA can be further enhanced by infusing significant volume of smoke using efficient smoke infusion pump.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors appreciate Volkswagen Stiftung funding initiative "Knowledge for Tomorrow – Cooperative Research Projects in Sub-Saharan Africa", for the financial support received, Konstanz University of Applied Sciences, Germany, and Jimma University, Ethiopia for providing the laboratory facilities to conduct this study.

REFERENCES

Annis PC, Morton R (1997). The acute mortality effects of carbon dioxide on various life stages of *Sitophilus oryzae*. Journal of Stored Products Research 33:115-124.

Bala BK, Haque MA, Hossain MA, Majumdar S (2010). Post Harvest Loss and Technical Efficiency of Rice, Wheat and Maize Production System: Assessment and Measures for Strengthening Food Security; Bangladesh Agricultural University: Mymensingh, Bangladesh.

Costa SJ (2014).Reducing Food Losses in Sub-Saharan Africa (Improving Post-Harvest Management and Storage Technologies of Smallholder Farmers); UN World Food Programme: Kampala, Uganda.

Davies S (2000). Nitric oxide signaling in insects. Insect Biochemistry and Molecular Biology 30:1123-1138.

Donahaye EJ, Navarro S (2000). Comparisons of energy reserves among strains of *Tribolium castaneum* selected for resistance to hypoxia and hypercarbia, and the unselected strain. Journal of Stored Products Research 36:223-234.

Inter-American Institute for Cooperation on Agriculture (IAICA) (2013). Post-Harvest Losses in Latin America and the Caribbean: Challenges and Opportunities for Collaboration; IICA: Washington, DC, USA.

Jayas DS, Jeyamkondan S (2002). Postharvest technology: modified atmosphere storage of grains meats fruits and vegetables. Biosystems Engineering 82:235-251.

Lefaux R (1968). Practical toxicology of plastics (International scientific series). CRC press, USA.

Liu YB (2013). Nitric oxide as a potent fumigant for postharvest pest control. Journal of economic entomology 106:2267-2274.

Moreno-Martinez E, Jiménez S, Vázquez ME (2000). Effect of *Sitophilus zeamais* and *Aspergillus chevalieri* on the oxygen level in maize stored hermetically. Journal of Stored Products Research 36:25-36.

Müller U (1997). The nitric oxide system in insects. Progress in neurobiology 51:363-381.

National Institute for Occupational Safety and Health (NIOSH) (20018). Immediately Dangerous to Life or Health (IDLH) Values. https://www.cdc.gov/niosh/idlh/630080.html. Accessed August 2018.

Navarro S (2010). Commercial application of oxygen depleted atmospheres for the preservation of food commodities. Woodhead Publishing 13:321-350.

Navarro S, Donahaye E, Calihoso FM, Sabio GC (1995). Application of mded atmospheres under plastic covers for prevention of losses in stored grain. Final Report submitted to U.S. Agency for International Development, CDR Project No. C7-053:32.

Nicolas G, Sillans D (1989). Immediate and latent effects of carbon dioxide on insects. Annual Review of Entomology 34:97-116.

Orang N, Tran H (2015). Effect of feedstock moisture content on biomass boiler operation. Tappi Journal pp. 629-637.

Shen G, Xue M, Wei S, Chen Y, Wang B, Wang R, Lv Y, Shen H, Li W, Zhang Y, Huang, Y, Chen H, Wei W, Zhao Q, Li B, Wu H, Tao S (2013). Influence of fuel moisture, charge size, feeding rate and air ventilation conditions on the emissions of PM, OC, EC, parent PAHs, and their derivatives from residential wood combustion. Journal of Environmental Sciences 25:1808-1816.

Sori W, Ayana A (2012). Storage pests of maize and their status in Jimma Zone, Ethiopia. African Journal of Agricultural Research 7:4056-4060.

United State Environment Protection Agency (USEPA) (2018). Nitrogen Dioxide Concentrations. https://www.epa.gov/roe/. Accessed April 2018.

Wang F, Jayas DS, White NDG, Fields P (2009). Combined effect of carbon monoxide mixed with carbon dioxide in air on the mortality of stored-grain insects. Journal of Stored Products Research 45:247-253.

Weinberg ZG, Yan Y, Chen Y, Finkelman S, Ashbell G, Navarro S (2008). The effect of moisture level on high moisture maize (*Zea mays* L.) under hermetic storage conditions-in vitro studies. Journal of Stored Product Research 44:136-144.

White NDG, Jayas DS (2003). Controlled atmosphere storage of grain. In: Chakraverty A; Majumdar AS, Raghavan GSW, Ramaswamy HS (Eds.). Handbook of Postharvest Technology. Cereals, fruits, vegetables, tea, and spices. Marcel Dekker Inc., New York 10:235-251.

White NDG, Jayas DS, Muir WE (1995). Toxicity of carbon dioxide at biologically producible levels to stored-product beetles. Environmental Entomology 24:640-647.

White NDG, Jayas DS (1991). Control of insects and mites with carbon dioxide in wheat stored at cool temperatures in non-airtight bins. Journal of Economic Entomology 84:1933-1942.

World Bank Group (1998). Nitrogen Oxides. Pollution Prevention and Abatement Handbook. https://www.ifc.org/wps/wcm/connect/.../HandbookNitrogenOxides.pdf?MOD. Accessed April 2018.

Zorya S, Morgan N, Diaz RL, Hodges R, Bennett B, Stathers T, Mwebaze P, Lamb J (2011). Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa; The international bank for reconstruction and development/the World Bank: Washington, DC, USA.