

Regulatory toxicology of alternative fumigants

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Abstract

Carbonyl sulfide (COS), ethyl formate (HCO₂C₂H₅, EF) and carbon disulfide (CS₂) are potential alternative fumigants for the protection of stored grains. At present EF is used as a fumigant of dried fruit, and CS₂ as a grain fumigant in China and in a region of Australia. Two toxicological issues that are relevant to the registration of these fumigants are the safety to workers potentially exposed to the fumigants, and the presence of residues in the commodity. There have been few studies of potential health effects of COS and EF in exposed workers but there is, by comparison, an extensive literature on the occupational exposures of workers to CS₂ during viscose rayon manufacture. Workers chronically exposed to CS₂ have shown neurotoxicological and ocular effects, and increased mortality from cardiovascular disease. However, many of the studies lack accurate CS₂ exposure level data and this has complicated the setting of safe occupational exposure levels.

In the present study, fumigation trials were conducted with COS, EF or CS₂ on wheat to determine the fate of fumigant residues. Wheat was treated with COS (24 g/t), EF (90 g/t) or CS₂ (42 g/t) in sealed, 50 tonne-capacity farm silos. On outloading COS-treated wheat had residue levels that were higher than untreated wheat, however the silo had been aerated for less than 2 h. The level of COS in fumigated wheat fell rapidly during transport and conditioning to reach levels indistinguishable from untreated wheat. The concentrations of EF in wheat had decayed to natural levels after a withholding period of 4 weeks. COS is present in untreated wheat at concentrations of 0.05 mg/kg and EF between 0.1–3 mg/kg, and both substances occur naturally at higher levels in other foods. Wheat treated with CS₂ had residues < 10 mg/kg after 24 h aeration of the wheat, substantially higher than the natural level of CS₂ (< 0.005–0.02 mg/kg) in untreated wheat. The presence of COS and EF residues at background levels after fumigation of wheat favours their registration as fumigants. The persistence of CS₂ residues and absence of a *Codex Alimentarius* maximum residue limit, in addition to occupational health and safety considerations, may limit

extensive use of CS₂ in the future.

Glossary of terms

ACGIH:	American Conference of Governmental Industrial Hygienists
COS:	Carbonyl sulfide
CS ₂ :	Carbon disulfide
DRG:	Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
EF:	Ethyl formate
IDLH:	Immediately Dangerous to Life or Health level
LC50:	Lethal concentration for 50% of test animals
MAK:	Maximum Concentration Values in the Workplace
MRL:	Maximum Residue Level
NIOSH:	National Institute for Occupational Safety and Health (USA)
NOHSC:	National Occupational Health and Safety Commission (Australia)
OSHA:	Occupational Safety and Health Administration (USA)
PEL:	Permissible Exposure Level
ppm:	parts-per-million
REL:	Recommended Exposure Limit
STEL:	Short-Term Exposure Limit
TLV:	Threshold Limit Value
TWA:	Time Weighted Average

Introduction

New and safer fumigants are being sought because of the ever-present prospect of resistance developing to existing fumigants and adverse effects of others on health and the environment. Isolated cases of resistance to phosphine have developed, for example, and methyl bromide is being phased out because of its depletion of stratospheric ozone. The fumigants carbonyl sulfide (COS), ethyl formate (EF) and carbon disulfide (CS₂) have been proposed as alternatives to methyl bromide and phosphine for the fumigation of grain.

COS has not been used previously as a grain fumigant and has had limited industrial use. EF is widely used as a solvent, a flavouring in foodstuffs, fragrance ingredient and

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as a fumigant of dried fruits and tobacco. The main uses of CS₂ are in the manufacture of viscose rayon and as an ingredient in the synthesis of, and as a solvent for numerous pharmaceutical, agricultural, mining and rubber chemicals. Currently there is some use of CS₂ as a grain fumigant in China and one region of Australia.

Registration of the alternative fumigants as agricultural chemicals will be required prior to their use or more widespread use in the case of CS₂. Two issues that are critical to this process are the occupational health and safety considerations for workers who may be exposed to the fumigants, and the presence of residues in fumigated wheat. The matter of fumigant residues is interesting as all three chemicals are present naturally in wheat, albeit at different concentrations (Desmarchelier and Ren, unpublished data). EF may be present in concentrations up to 3 mg/kg, COS at levels up to 0.05 mg/kg while CS₂ is present in trace quantities in wheat. This paper discusses these issues in the context of possible registration of the alternative fumigants.

Occupational health and safety of alternative fumigants

COS is a gas at room temperature and pressure whereas EF and CS₂ are liquids that have high vapour pressures and are therefore readily volatilised.

Flammability

COS, EF and CS₂ are flammable substances given the optimal conditions, however, some methods of their use in grain fumigation may reduce their flammability risk. The lower and upper flammable (explosive) limits (LFL/UFL) for COS in air are 12 and 28.5% (v/v) (Sax and Lewis, 1986) and are well above the concentration required for control of insects. Pure EF has LFL/UFL of 2.8 and 16% but the proposed formulation of EF for grain fumigation is a 4% aqueous solution of EF. The dilute solution of EF substantially reduces the flammability risk. CS₂ has LFL/UFL of 1.3 and 50% and as it applied as a neat liquid for grain fumigation it poses a flammability risk.

Exposure standards

The health of workers exposed to chemicals during work hours may be protected by regulatory standards governing air concentrations. The exposure standard is a concentration of a substance in the air within a worker's breathing zone, exposure to which should not cause adverse health effects or discomfort to most workers (NOHSC, 1995). The standard may be altered based on new information about the health effects of the substance. Exposure standards are expressed as parts-per-million (ppm) on a volume basis, and the most widely recognised are the threshold limit values (TLV®) which are produced by the American Conference of

Governmental Industrial Hygienists (ACGIH) and adopted by many other countries. However, there are many organisations which produce exposure standards in different countries and a list of the various exposure standards for the alternative fumigants is given in Table 1. Most occupational exposure standards are based on an 8 h per d, 5 d per wk exposure duration which is known as the time weighted average (TWA).

Table 1. Occupational exposure standards (in ppm) for alternative fumigants in different countries.

Regulatory Agency	COS	EF	CS ₂
Australia TLV (NOHSC)	n. a.	100	10[skin] ^a
Germany MAK (DGF)	n. a.	100	10[skin]
U. S. A. TLV (ACGIH)	n. a.	100	10[skin]
PEL (OSHA)	n. a.	100	4 ^b [skin]
REL (NIOSH)	n. a.	100	1[skin]
STEL (NIOSH)	n. a.	n. a.	10
IDHL (NIOSH)	n. a.	1,500	500

n. a. not assigned

a [skin] notation signifies that this exposure route may lead to substantial absorption

b non-enforceable limit due to a US court decision. Transitional PEL of 20 ppm currently applies

TLV values are on a TWA basis

See Glossary for explanation of acronyms

Source of values ACGIH (1993)

An exposure standard has not been assigned for COS. This may be due to the limited use of COS in industry or the lack of sufficient information on which to base a standard. A TLV of 10 ppm has been recommended in the material safety data sheet for COS which is also the exposure standard for hydrogen sulfide (BOC, 1996). It has been shown that COS is converted to hydrogen sulfide in rats, and it is the formation of hydrogen sulfide that is considered to be the toxic action of COS (Chengelis and Neal, 1980).

The occupational exposure standards for EF (TLV 100 ppm) are much higher than those of the other fumigants in Table 1, and higher than methyl bromide and phosphine that have TLVs of 5 and 0.3 ppm, respectively (ACGIH, 1993).

Exposure standards for CS₂ vary depending on the regulatory body that has set them. While the TLV level is similar in different countries (10 ppm), two regulatory bodies in the US, the National Institute for Occupational Safety and Health (NIOSH) and Occupational Safety and Health Administration (OSHA), have reduced the exposure standard for CS₂ following review of the epidemiological

literature of CS₂-related effects in workers. OSHA reduced the Permissible Exposure Level (PEL) to 4 ppm (12 mg/m³) with a STEL of 12 ppm (36 mg/m³) but this level is currently unenforceable pending a court decision. Until that issue is decided, the transitional PEL defaults to the original value of 20 ppm, 30 ppm ceiling and a 100 ppm (30 min) maximum peak. NIOSH reduced the Recommended Exposure Limit (REL) to 1 ppm by attaching a 10-fold safety factor to the lowest concentration thought to increase risk of coronary heart disease (NIOSH, 1977). The PELs established by OSHA are the only exposure standards enforceable by law in the U. S.

Adverse health effects of alternative fumigants

Continuous exposure to COS gas at 15 – 50 ppm concentrations will generally cause irritation to mucous membranes in addition to headache, dizziness and nausea. Exposure to concentrations of COS between 200 – 300 ppm may lead to respiratory arrest, coma and unconsciousness (BOC, 1996). In mice, the lethal concentration to 50% of the test population (LC50) in 35 min was 1200 ppm (Sax and Lewis, 1986). There have been few documented cases of human exposures to COS but the death of a worker entering a bunker was attributed to COS (Thuess et al., 1968). COS is metabolised in rats to carbon dioxide and hydrogen sulphide with the latter compound proposed to be the toxic agent (Chengelis and Neal, 1979; 1980). Hydrogen sulfide is highly toxic and may be fatal at high concentrations. The 60 min LC50 for hydrogen sulfide in rats is 444 ppm (Tansy et al., 1981) and the approximate lethal concentration in humans is 600 ppm for a 30 min exposure (Lefaux, 1968).

EF is an irritant to nose, throat and lungs at levels >300 ppm. At higher concentrations, depression of the central nervous system, nausea, headache, fatigue, and loss of coordination may be observed. The LC50 of EF in rats was 8000 ppm after a 4 h exposure (Anon, 1978). The proposed formulation of grain fumigant EF is an aqueous solution (4% w/w) and this mixture is unlikely to cause significant skin irritation or sensitisation (Anon, 1978), however, skin and eye protection should be worn as it is good practice to minimise exposure to chemicals. EF was not carcinogenic in animal studies (Roe and Salaman, 1955; Rady et al., 1981), nor was it mutagenic (NTIS, 1976; Zimmerman et al., 1976).

Adverse effects of CS₂ may be categorised into hyperacute, acute, subacute and chronic by the duration and concentration of the exposure (WHO, 1979). Inhalation of very high concentrations of CS₂ (> 3000 ppm) leads to hyperacute poisoning, rapid coma formation and death. Acute exposure to 500 – 1000 ppm CS₂ for relatively short periods of time may result in permanent effects on the central nervous system which are manifested by mood and

personality disturbances including excitability, confusion, anger, insomnia, psychosis and suicide (Wood, 1981). These symptoms are experienced during exposures well above those of the present occupational exposure standards. Chronic exposure to CS₂ in workers in the viscose rayon industry, as detailed below, has led to effects on the eye and to the central and peripheral nervous systems, and to cardiovascular and reproductive effects. Other effects of CS₂ exposure observed in exposed workers include hearing loss, irregularities of the menstrual cycle and increase in miscarriages although there have been conflicting reports of some of these effects in workers, and the possible concomitant exposure with other gases has not been addressed (WHO, 1979; Beauchamp et al., 1983).

Long-term exposure to CS₂ in relatively high doses (32 to 128 ppm), has resulted in changes in eye structure and function (Beauchamp et al., 1983). Additional studies of Japanese, Finnish and Dutch rayon workers exposed to lower levels of CS₂ for at least one year, showed early signs of ophthalmological damage. However, the studies showed different spectra of effects in workers from different countries (Beauchamp et al., 1983, Vanhoorne et al., 1996).

Chronic exposures (ca. 20 years) to CS₂ at concentrations up to 70 ppm have resulted in definite indications of neuropathy such as numbness or tingling, muscle weakness or pain and loss of sensation in the extremities. The symptoms were present up to 10 years after exposure to CS₂ ceased. The reported symptoms of central nervous system damage include headache, sleep disturbances, general fatigue, loss of libido and Parkinsonism in workers exposed to CS₂ at levels generally higher than the TLV (Beauchamp et al., 1983).

An increased risk of coronary heart disease has been reported in workers exposed to CS₂ concentrations close to the TLV (10 – 30 ppm). Although advanced age and elevated diastolic blood pressure were the main risk factors predisposing to coronary heart disease, CS₂ exposure was shown to contribute to the overall risk (Beauchamp et al., 1983). Many of the epidemiological studies on which these findings were based had inadequate CS₂ concentration monitoring which has made it difficult to ascertain the increased risk of coronary heart disease at levels near the current TLV. The rate of mortality from coronary heart disease decreased when occupational exposure measures lowered the air concentration to below 10 ppm. A recent study of low level CS₂-exposed workers have found little difference in coronary heart disease risk compared with unexposed workers (Drexler et al., 1996).

Some studies of the effect of CS₂ exposure on male reproduction have shown significant effects on reproductive endpoints such as decreased spermatogenesis, lower serum levels of endocrine hormones and reduced libido, whereas

other studies found no differences in semen quality compared with unexposed controls (Schrag and Dixon, 1985). In a recent study, libido and potency were significantly reduced in workers occupationally exposed to CS₂ at levels above the TLV, in comparison with age-matched unexposed controls, but the quality of the semen and the number of children of the workers were not significantly different between the two groups (Vanhoorne et al., 1994).

It is not known how similar the exposure scenarios for workers in rayon manufacture are to potential exposures of workers during grain fumigation or how a different exposure pattern may affect the risk of adverse effects with its use. There is a high risk of permanent damage to the nervous system in grain fumigators using CS₂ without adequate skin protection or suitable respirators. That is, unprotected grain fumigators may be exposed to higher concentrations of CS₂ than workers in rayon manufacture as they are more likely to be handling liquid CS₂ concentrate. Most exposure standards for CS₂ include a [skin] notation which signals that dermal exposure can have an important contribution to overall exposure. Skin absorption of CS₂ can also result in irritation or blistering and splashes in the eye can cause immediate severe irritation.

Biomonitoring of occupational fumigant exposure

It is possible to measure the absorbed dose of CS₂ in an exposed worker, in addition to ambient air concentrations by measuring the presence of CS₂ metabolites in the urine. The metabolite 2-thiothiazolidine-4-carboxylic acid (TTCA) accounts for approximately 3% of the absorbed human dose of CS₂, and is used to monitor occupational exposures to CS₂ (Van Doorn et al., 1981). In many studies, the level of TTCA in urine has been correlated to the magnitude of exposure to CS₂ by ambient monitoring during the workshift (e.g. Meulin et al., 1990, Drexler et al., 1994).

The concept of biomonitoring for EF exposure has not been reported. In the case of EF, biomonitoring may not be feasible as EF is rapidly hydrolysed once it enters the body to form ethanol and formate. Ethanol monitoring would be subject to interference from other exposure sources and the measurement of formate as a product of EF in blood or urine of exposed workers is complicated by the presence of endogenously produced formate. The mean concentration of formate in human serum is 13 mg/L in serum, and formate is excreted at the rate of 0.5 mg/h in urine (d'Alessandro et al., 1994).

The implementation of biological monitoring of COS exposure will require an understanding of the metabolic fate of the fumigant in man, and the identification and ready detection of a suitable product in saliva or urine. COS is a naturally occurring substance both in the atmosphere and in some foods, particularly vegetables of the Brassica genus (broccoli, cabbage etc) (Desmarchelier and Ren,

unpublished data). Therefore the development of a biomonitoring method for occupational COS exposure will have to address background exposure from natural sources.

Alternative Fumigants Trial-monitoring Exposure, Residues and Efficacy

Field-scale experiments of COS, EF and CS₂ fumigation of wheat were conducted by CSIRO Division of Entomology (J. Desmarchelier, Chief Investigator) for the purpose of obtaining efficacy and residue data that would support future registration of the fumigants and monitoring worker exposure.

Chemicals

COS was obtained from BOC, Australia, EF was a gift of ICI Australasia and CS₂ was purchased from Ajax Chemicals, Australia. The purity of COS was determined to be 95% prior to purification by passage of the gas through copper sulfate solution to remove hydrogen sulfide contamination.

Fumigation protocols

Welded-steel cylindrical farm silos of 50 tonne capacity, fitted with aeration ducts were sealed with silicone and tested for air-tightness. Australian Standard White wheat (36 t) of unspecified moisture content was loaded into the silo and purified COS (400 L) was added to the headspace above the wheat. The final application rate of COS was 24.4 g/t wheat and the fumigation proceeded for 7 d. The silo was aerated for up to 2 h until the intra-silo concentration reached the TLV (10 ppm) and then the wheat was outloaded.

In a separate experiment, aqueous EF, 4% (w/w), was dripped onto wheat (40 t) as it was loaded into the silo. The final concentration of EF in wheat was 90 g/t and the fumigated wheat was withheld for 4 wk prior to outloading.

In a further trial, CS₂ was added as a neat liquid (1.2 L) via an external funnel and tube to hessian sacking placed on the surface of the wheat (36 t) in a sealed silo. The total rate of CS₂ application was 41.6 g/t. The fumigation proceeded for 6 d, the silo was aerated for 24 h until the intra-silo concentration reached the TLV (10 ppm) and then the wheat was outloaded. Intra-silo concentrations of COS and CS₂ were measured by sampling of gas via nylon lines that were inserted into the silo at multiple positions in the wheat mass and analysis of the gas by gas chromatography. The appropriate respirator and skin protection were used during the handling of fumigant concentrates and mixtures.

Monitoring exposure to fumigants

Multiple measurements were taken of COS, EF and CS₂

concentrations in the air around the silos under fumigation. A radius of 3 m around each farm silo and a height of 1.5 to 1.9 m from the ground was determined to be the workspace for potential exposure of workers to fumigants. Around 10 – 20 measurements of air in the workspace were sampled by drawing air into Tedlar® bags and COS, EF and CS₂ measured by gas chromatography (GC). The analytical methods used were capable of detecting as low as 10 ppb EF and 1 ppb for COS and CS₂ (0.01% of the respective TLVs).

At the flour mill, some sampling of air was carried out to determine fumigant concentrations originating from CS₂-fumigated wheat. Air samples were drawn from the surface of CS₂-fumigated wheat held in 'dirty' bins into Tedlar® bags, at the bottom of the 'dirty' bins and at the surface of the bin containing conditioned wheat (see Sampling and Analysis of Wheat and Milled Products for a description of the sampling stages). These sites were accessible to workers in the mill.

Sampling and analysis of wheat and milled products for fumigant levels

Sampling of wheat for fumigant analysis was carried out:

- (1) of outloaded wheat from the silo as it was loaded into bags
- (2) at the flour mill, from the receival route into the holding 'dirty' container
- (3) at the flour mill, during transfer of the cleaned wheat to the 'clean' container
- (4) of wheat after it was conditioned (18 h moistening treatment of grain) at the mill
- (5) of milled fractions, these were commercial grade flour, pollard finished flour, pollard, germ and bran.

At all sampling stages, approximate mid-stream samples of wheat (60 g) or milled fractions (10 g) were taken. Extraction solvents e. g. methanol for EF determination, were added to wheat or milled fractions after sampling thereby initiating the analytical process as soon as possible. COS and CS₂ were analysed using the official analytical method (Daft 1984, 1988) and EF was extracted into methanol using a method for multi-residue analysis (Sharp et al., 1988).

Results and Discussion

Workspace exposure monitoring

The air concentrations of fumigants in the workspace, an area defined by a radius of 3 m from the silo at a height of 1.5 – 1.9 m, did not exceed 0.01% of the respective current TLV for COS, EF or CS₂ during the fumigation phase of the trials. This demonstrates that fumigation with COS, EF and CS₂ can be carried out and the air concentrations remain well within the exposure standards

when sealed storage is used.

Elevated exposure to fumigants may occur when handling concentrated fumigants. One circumstance during the alternative fumigant trial where the workspace air concentration of EF exceeded the TLV (100 ppm) was during refilling of the container of 4% EF solution to be applied as a drip, however, the exposure to the experimenter was minimal as he was wearing an appropriate respirator and skin protection. Also, during the application of CS₂ to the grain, significant exposure above the TLV is likely where protective equipment is not used.

At the flour mill during processing of the wheat, the air concentrations of CS₂ were highest at the bottom of 'dirty' bins containing CS₂-fumigated wheat but the value (0.62 ppm) was substantially below the current TLV of 10 ppm. The air concentration of CS₂ at the surface of the conditioned wheat was 0.15 ppm.

Levels of fumigant in fumigated and untreated wheat

The levels of COS, EF and CS₂ in untreated and fumigated wheat on outloading from the silos, after transport to the flour mill and within the mill, after conditioning and in the milled fractions, are given in Figure 1 (A, B and C, respectively).

COS is naturally present in wheat at levels of 0.05 mg/kg (Desmarchelier and Ren, unpublished data). The levels of COS in COS-fumigated wheat on outloading was substantially higher than the natural levels in wheat but the concentration of COS rapidly declined in the fumigated wheat during transport and processing (Figure 1A). Fumigated wheat was aerated for less than 2 h before outloading and it is anticipated that extending aeration time will result in COS levels falling to natural levels in fumigated wheat at outloading. At the stage of conditioning and in the milled fractions, COS-fumigated wheat had the same level of COS as the untreated wheat.

In wheat fumigated with EF, the concentrations of EF were similar for untreated and EF-fumigated wheat that had been withheld for 4 wk, during all sampling stages (Figure 1 B). The natural level of EF in wheat ranges between 0.1 – 3 mg/kg depending on the wheat variety, age and storage conditions (Desmarchelier and Ren, unpublished data).

Wheat fumigated with CS₂ had residues of 6.4 mg/kg on outloading after 24 h aeration of the wheat. Although the CS₂ residues were below the Australian maximum residue limit (MRL) of 10 mg/kg, they were substantially higher than the natural level of CS₂ (< 0.005 – 0.02 mg/kg) in untreated wheat (Desmarchelier and Ren, unpublished data). The CS₂ residues persisted throughout the transportation, conditioning and milling stages with the highest residues of milled fractions found in the germ (Figure 1 C).

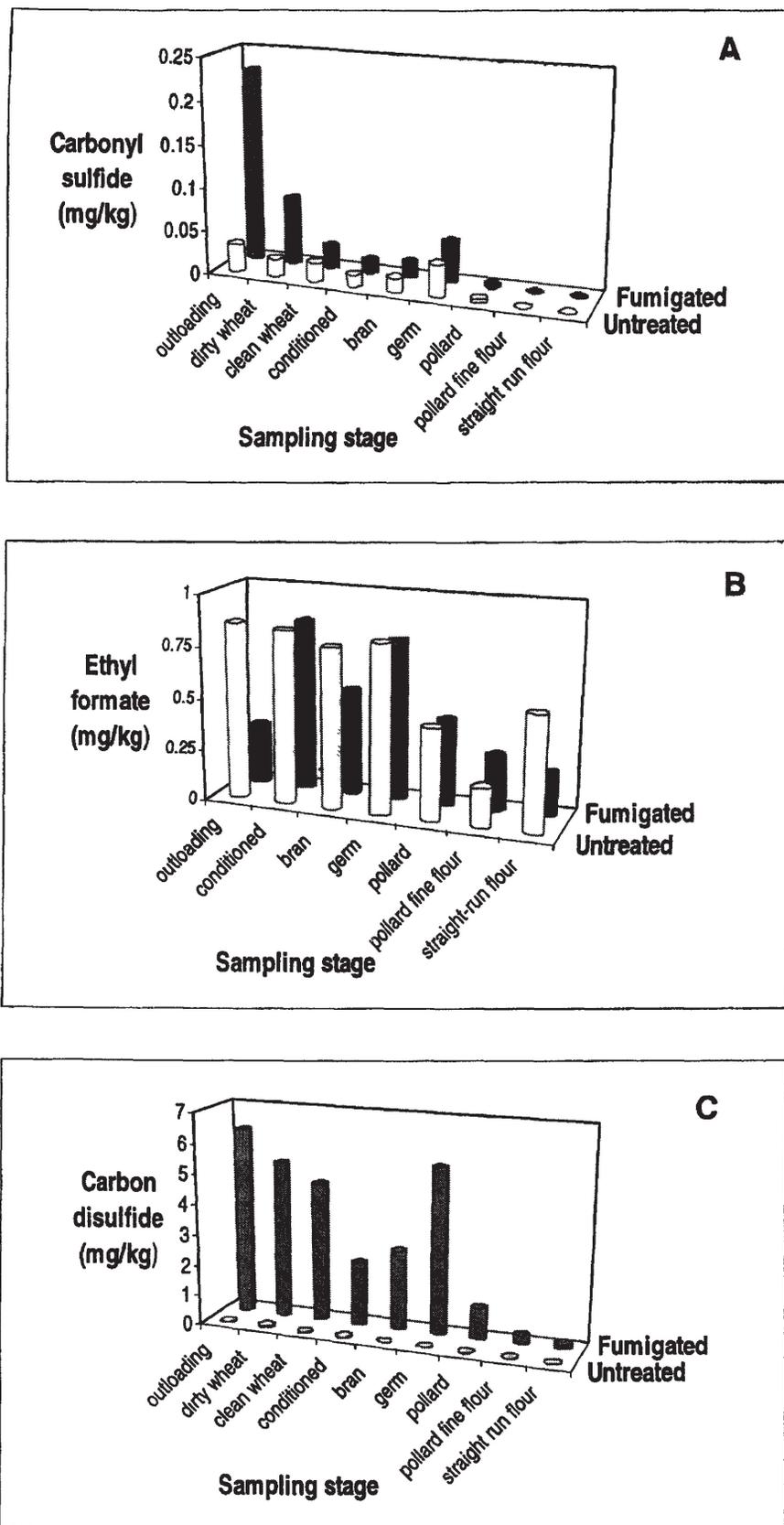


Fig. 1. Levels of fumigant (and interfering substances) in wheat fumigated with (A) COS (B) EF or (C) CS₂ compared with natural levels in untreated wheat

Efficacy of fumigations

The applied levels of fumigant were efficacious in killing *Tribolium castaneum* (adults and larvae), *Rhyzopertha dominica* (mixed age cultures), *Sitophilus oryzae* (mixed age cultures) that were placed in traps in the silos prior to COS and CS₂ fumigation, or after loading of EF-treated wheat. All insect stages were killed by the fumigation regimes except in the EF fumigation where two adult *S. oryzae* (0.26% of total *S. oryzae*) survived fumigation. After incubation of the surviving adults for a further 28 d at 30°C, 31 progeny were produced.

Where sufficient aeration or withholding periods are used, fumigation of wheat with COS and EF can result in levels of these fumigants present that are indistinguishable from the natural levels. The optimal aeration times and withholding periods for other grains fumigated with the alternative fumigants are currently being investigated. The moisture content of grain may also affect the persistence of EF residues. In this field trial, a 4 wk withholding period was proposed for EF-fumigated wheat based on the slower decay of EF in cool, dry grain. The natural levels of COS and EF in commodities will need to be carefully identified to ensure the levels are not exceeded after fumigation and appropriate withholding periods. The registration process may be simplified for fumigants whose residue levels in the fumigated commodity is indistinguishable from the natural level as there is less requirement for long term feeding studies to assess the toxicity of persistent residues.

The benefits and disadvantages of potential alternatives to methyl bromide and phosphine for grain fumigation have been discussed by various researchers (e. g. Bond 1984; Banks 1996). Among the perceived drawbacks of CS₂ as a grain fumigant were its high flammability and the loss of *Codex Alimentarius* 'guideline' tolerance (full maximum residue limit at Codex was never attained for CS₂). To obtain a Codex MRL for CS₂ full toxicological assessment of the chemical, including long-term feeding studies in rodents, would be required to ensure that CS₂ residues in commodities were safe to consume, in addition to proof of efficacy of CS₂ in field trials. Presently, the lack of mammalian toxicological data on which to base an application for international registration, and the cost of toxicology studies, will limit the future use of CS₂ as a grain fumigant. The safety to workers potentially exposed to CS₂ will need to be carefully considered in the light of the extensive knowledge of adverse effects from occupational exposure to CS₂. The revised 1989 PEL exposure standard for CS₂ in the U.S. (4 ppm) is lower than the current TLV (10 ppm) and signals the trend to reduce occupational exposures. Industries where workers are exposed to CS₂ will need to consider whether they can comply with the lower exposure standard when they are introduced.

Conclusion

On the basis of occupational health, the presence of residues at natural levels and efficacy it is worth pursuing registration for COS and EF as grain fumigants, but for CS₂, persistent residues and occupational health and safety considerations may limit extensive use of CS₂ in the future.

References

- American Conference of Governmental Industrial Hygienists (ACGIH), 1993. Guide to Occupational Exposure Values-1993. Cincinnati, Ohio, ACGIH, 122p.
- Anonymous, 1978. Ethyl formate. Monographs on fragrance raw materials. Food & Chemical Toxicology, 16, 737 – 739.
- Banks, H. J. 1996. Fumigation-an endangered technology? In: Highley, E., Banks, H. J., Wright, E. J. and Champ, B.R. ed., Proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, April 1994, 2 – 6.
- Beauchamp Jr, R. O. Bus, J. S., Popp, J. A., Boreiko, C. J. and Goldberg, L. 1983. A critical review of the literature on carbon disulfide toxicity. CRC Critical Reviews in Toxicology, 11, 169 – 278.
- BOC, 1996. Carbonyl sulfide. Material Safety Data Sheet, 7/6/96, 6p.
- Bond, E. J. 1984. Manual of fumigation for insect control. Rome, FAO Plant Production and Protection Paper No. 54, 432p.
- Chengelis, C. P. and Neal, R. A. 1979. Hepatic carbonyl sulfide metabolism. Biochemical and Biophysical Research Communications, 90, 993 – 999.
- Chengelis, C. P. and Neal, R. A. 1980. Studies of carbonyl sulfide toxicity: metabolism by carbonic anhydrase. Toxicology and Applied Pharmacology, 55, 198 – 202.
- Daft, J. 1984. Determining multifumigants in whole grains and legumes, milled and low-fat products, spices, citrus fruits and beverages. Journal of the Association of Official Analytical Chemists, 70, 734 – 739.
- Daft, J. 1988. Rapid determining of fumigant and industrial chemical residues in food. Journal of the Association of Official Analytical Chemists, 71, 748 – 760.
- D'Alessandro, A., Osterloh, J. D., Chuwers, P., Quinlan, P. J., Kelly, T. J. and Becker, C. E. 1994. Formate in serum and urine after controlled methanol exposure at the threshold limit value. Environmental Health Perspectives, 102, 178 – 181.
- Drexler, H. Goen, T. Angerer, J. Abou-el-ela, S., and Lehnert, G. 1994. Carbon disulphide. I. External and internal exposure to carbon disulphide of workers in the viscose industry. International Archives of Occupational

- and Environmental Health, 65, 359–365.
- Drexler, H. Ulm, K., Hardt, R., Hubmann, M., Goen, T., Lang, E., Angerer, J. and Lehnert, G. 1996. Carbon disulphide. IV. Cardiovascular function in workers in the viscose industry. *International Archives of Occupational and Environmental Health*, 69, 27–32.
- Lefaux, R. 1968. *Practical toxicology of plastics*. Cleveland, Chemical Rubber Co., 207.
- Meulin, W. J. A., Bragt, P. C. Braun, C. L. J. 1990. Biological monitoring of carbon disulfide. *American Journal of Industrial Medicine*, 17, 247–254.
- National Institute for Occupational Safety and Health (NIOSH) 1977. Criteria for a recommended standard... occupational exposure to carbon disulfide. Washington DC, NIOSH, May 1977, 186p.
- National Technical Information Service (NTIS) 1976. Mutagenic evaluation of compound FDA 75–49, 000109–94–4, ethyl formate, NTIS report (PB-266 890), 46p.
- National Occupational Health and Safety Commission (NOHSC) 1995. Exposure standards for atmospheric contaminants in the occupational environment: guidance note on the interpretation of exposure standards for atmospheric contaminants in the occupational environment (NOHSC: 3008). NOHSC, Canberra, 3rd ed.
- Rady, P., Arany, I., Uzvoelgyi, E., and Bojan, F. 1981. Activity of pyruvate kinase and lactic acid dehydrogenase in mouse lung after transplacental exposure to carcinogenic and non-carcinogenic chemicals. *Toxicology Letters*, 8, 223–227.
- Roe, F. J. C., and Salaman, M. H. 1955. Further studies on incomplete carcinogenesis: triethylene melamine (T. E. M.), 1, 2-benzanthracene and β -propiolactone, as initiators of skin tumour formation in the mouse. *British Journal of Cancer*, 9, 177–203.
- Sax, N. I. and Lewis, R. J. (1986) *Rapid guide to hazardous chemicals in the workplace*. New York, Van Nostrand Reinhold, II. 7th ed.
- Schrag, S. D. and Dixon, R. L. 1985. Occupational exposures associated with male reproductive dysfunction. *Annual Reviews of Pharmacology and Toxicology*, 25, 567–592.
- Sharp, G. J., Brayan, J. G., Dilli, S., Haddad, P. R. and Desmarchelier, J. M. 1988. Extraction, clean-up and chromatographic determination of organophosphate, pyrethroid and carbamate insecticides in grain and grain products. A review. *Analyst*, 113, 1493–1507.
- Tansy, M. F., Kendall, F. M., Fantasia, J., Landin, W. E., Oberly, R. 1981. Acute and subchronic toxicity studies of rats exposed to vapors of methyl mercaptan and other reduced sulfur compounds. *Journal of Toxicology and Environmental Health*, 8, 71–88.
- Thiess, A. M., Hey, W., Hofmann, H. T. and Oettel, H. 1968. Zur toxicitat des kohlenoxydsulfids. *Archiv fur Toxikologie*, 23, 253–263.
- Van Doorn, R., Delbressine, L. P. C., Leijdekkers, C. M., Vertin, P. G. and Henderson, P. H. 1981. Identification and determination of 2-thiothiazolidine-4-carboxylic acid in urine of workers exposed to carbon disulfide. *Archives of Toxicology*, 47, 51–58.
- Vanhoorne, M., Comhaire, F., De Bacquer, D. 1994. Epidemiological study of the effects of carbon disulfide on male sexuality and reproduction. *Archives of Environmental Health*, 49, 273–278.
- Vanhoorne, M., De Rouck, A., De Bacquer, D. 1996. Epidemiological study of the systemic ophthalmological effects of carbon disulfide. *Archives of Environmental Health*, 51, 181–188.
- World Health Organisation (WHO) 1979. Carbon disulfide. *Environmental Health Criteria*, Geneva, WHO, No. 10, 100p.
- Wood, R. W. 1981. Neurobehavioral toxicity of carbon disulfide. *Neurobehavioral Toxicology and Teratology*, 3, 397–405.
- Zimmermann, F. K., Mayer, V. W., Scheel, I., Resnick, M. A. 1985. Acetone, methyl ethyl ketone, ethyl acetate, acetonitrile and other polar aprotic solvents are strong inducers of aneuploidy in *Saccharomyces cerevisiae*. *Mutation Research*, 149, 339–351.