Fumigation and Controlled Atmospheres as Components of Integrated Commodity Management in the Tropics

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Abstract

This paper outlines fumigation practices in central storage systems handling bagged commodities in the tropics. Problems caused by failure of whole-store treatments leading to recommendations for more extensive use of sheet fumigation are described. The requirements for successful sheet fumigation are defined in terms of final gas concentration for carbon dioxide, methyl bromide, and phosphine. Practical methods to achieve these targets using sealed stacks and improved sheet fumigation practice and alternate fumigation methods are described. The paper concludes with a short account of alternative infestation control methods and the need to integrate them into commodity storage systems as a means to ensure the continued effective use of fumigation.

IN the tropics almost all grain and other durable commodities held in central storage are stored in bags (Halliday and Calverley 1986), without the protection of admixed insecticides. If held in keeping with good storage practice, stocks are usually disinfested when they enter storage. This is usually achieved by fumigating the bags immediately before or after they are stacked. Thereafter, a combination of preventive measures, comprising both good storage hygiene and regular spray treatments with residual insecticides may be used to protect the commodity against reinfestation (Webley 1986a,b). This treatment eventually fails, because it does not provide an effective barrier to insects passing through the treated surfaces into the centre of the stacked commodity where populations can build up (Webley 1986b). Other insecticidal methods for protecting bag-stacked commodities, such as layer-by-layer treatments (Dick 1987), insecticide impregnated textile stack covers (Hayward 1984) or permanently enclosing a stack under unsealed plastic sheets (McFarlane 1980), are more effective, but are still unable to provide complete protection against infestation. Eventually insect numbers build up to levels at which the damage that they cause is unacceptable and curative action must be taken.

Fumigation is the preferred method of infestation control in many instances, because the process is rapid and can be undertaken without moving the commodity. Fumigation is usually carried out by temporarily enclosing the stack under gas-proof sheets while the fumigant is applied using a technique known as 'sheet fumigation'.

In bag storages, this cycle of preventive, or prophylactic, treatments with insecticides followed by curative, or intervention, fumigations may be repeated a number of times whilst a commodity is stored.

Frequently, there is a need to simultaneously fumigate most or all of the stacks in a storage when these either become infested (Mathur 1986), or there is a requirement to eradicate pests subject to quarantine restrictions. Under such circumstances, whole-store fumigation offers a number of advantages over conventional 'sheet fumigation' and has consequently

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attracted considerable attention. Unfortunately, the majority of storages in the tropics are unsuitable for this technique because they cannot be sealed and made sufficiently gas-tight for effective fumigation (Hayward 1984; Harnisch 1988). Despite this, whole-store fumigations have been carried out. Where the technique has been applied in poorly sealed storages over a period of time, high levels of fumigant resistance to phosphine have been reported in a number of stored product pest insects (Tyler et al. 1983).

A small but increasing quantity of grain is stored in bulk, as opposed to bag, in the central storage systems operating in the tropics (Champ and Highley 1988; Anon 1988a). A wide range of storage structures is in use for this purpose.

Airtight underground storages were successfully utilised for hermetic storage of bulk maize in Tanzania and Malawi from 1949 to 1955 (Hall et al. 1956; Pattinson 1969). Underground hermetic storages with capacities for up to 1000 tonnes of grain are still in use in Somalia (de Lima 1990; Watt 1969), the People's Republic of China (Zhu Renkang 1988) and Argentina. Semi-underground, hermetic 'Cyprus' bins are used in Kenya for long-term, bulk storage of strategic food reserves (de Lima 1980a).

Where sealable silos have been erected, the option to seal has not usually been exercised. Sealed vertical steel silos of various designs with the potential for hermetic storage have been installed in Morocco and Venezuela and in several West African francophone countries (Ransome 1960). In the Ivory Coast, a number of these are presently in use with controlled atmospheres (H.J. Banks, pers. comm.). Similar silos have been installed elsewhere in the tropics, where their potential for use either as hermetic storages or with controlled atmospheres has not been utilised. The practical difficulties of maintaining the required air-tightness in hermetic structures has led to declining interest in this method of storage in the tropics (Halliday and Calverley 1986).

There has, however, been a greater interest in the use of controlled atmospheres, e.g. in Cameroon, where Lipp silos have been used with controlled atmospheres (Fleurat-Lessard 1986). Use of controlled atmospheres has also been extended to bag storage. In Indonesia, grain held in conventional bag storages is stored under controlled atmospheres retained within well-sealed plastic enclosures (Yun C. Nataredja and Hodges 1990) known as 'sealed stacks' (Annis 1990b). Elsewhere in Southeast Asia, sealable bag storages have been constructed specifically for use with controlled atmospheres (Muda et al. 1988; Samarasinghe et al. 1987).

When a commodity is finally removed from storage, it may again have to be disinfested to comply with international regulatory or trade requirements. This final fumigation is usually carried out in-store; though it can also be undertaken in-transit (Bond 1990; Davis 1986) for which controlled atmospheres are also used (Adamovsky and Mordkovich 1989).

Current Fumigation Practice

The technique of fumigation under gas-proof sheeting, or 'sheet fumigation' (Burns Brown 1954), is the most widely used method for disinfesting bagged commodities stored in the tropics. The process was formerly carried out with hydrogen cyanide, but use of this gas diminished as supplies of methyl bromide became more abundant in the 1940s (Ismail bin Shamsudin et al. 1981). Phosphine, introduced widely in the 1960s, is now the most commonly used fumigant in the tropics, because of its low cost, ease of handling and effectiveness (Hayward 1984; Krishnamurthy 1973). It is normal in areas some distance from regional centres and capital cities to find that choice of fumigant is restricted to phosphine, whereas methyl bromide is used only in larger centres where the required expertise for its application is available. Phosphine tends now to be presented as the fumigant of first choice (Anon 1985; Webley 1984; Reichmuth 1988) and in some countries has totally replaced methyl bromide (Taylor 1986). One long-term consequence of this trend, both in the public and private sectors, has been an increasing use of phosphine by fumigators lacking experience of the more rigorous requirements of methyl bromide fumigation. Inexperience of the requirement for good sealing, in particular, has contributed to the substandard fumigations that have been the cause of considerable concern (GASGA 1986).

Harris (1981) and Harnisch (1988) list a number of reasons for unsatisfactory fumigations in tropical countries including:

- poor equipment;
- lack of fumigator training;

- need for management awareness;
- poor fumigation techniques;
- incorrect exposure periods;
- underdosing;
- the need to integrate pest control operations;
- poor stack preparation; and
- failure to monitor fumigant concentrations.

Substandard fumigation practices continue to occur. It is common to find fumigations where:

- sheets are simply laid flat over one another, with no attempt made to roll and seal them together;
- sheets are not sealed to the floor; and
- phosphine-generating compounds are applied directly to a commodity without the use of any form of enclosure.

While many of these problems are directly attributable to poor training and lack of management awareness, the economic pressures exerted on private fumigation contractors are also important and infrequently reported. For example, the necessity to reduce fumigant loss downwards through the floor by building stacks on a gas-proof surface, is well known (Burns Brown 1954) but often overlooked in practice. In central storages, where fumigators are frequently involved as stacks are built, there is usually an awareness of this requirement (U Hla Myint and U San Maung 1986). In the private sector, however, contract fumigators rarely view a stack before treating it, and it is not unusual to find them built on pallets laid directly onto the ground.

Those in charge of the commodity are normally reluctant to restack correctly and, in the event of a fumigator's unwillingness to undertake the work, the services of another less professional operator will be sought. Competing contractors may also attempt to recoup price cuts by reducing the dose of fumigant applied to well below the recommended dosage. Additionally, influenced by the claims of manufacturers of phosphine-generating compounds, fumigators have tended to reduce exposure periods to compete with rival products (Winks 1986a) and the speed of methyl bromide fumigations. More recently the introduction of magnesium-based phosphine-generating compounds has been accompanied by further recommendations for reduced exposure periods (private communication). These recommendations are spurious because they cannot produce a complete kill of the tolerant stages of pest insects (Winks 1986a).

Such malpractices are not only the direct cause of fumigation failures but can eventually lead to the development of fumigant tolerance in pest insects by repeated exposure to sublethal doses. This has already occurred where whole-store fumigations have been carried out in improperly sealed storages.

Whole-store fumigation has been seen to be simpler to implement than 'sheet fumigation' but was cumbersome when applied using methyl bromide. The advent of phosphine, with its ease of application (Hayward 1984), made it possible to use the technique in situations, where formerly it had been impractical. Whole-store fumigations have been successfully carried out with methyl bromide since 1966 in Nigeria, in cocoa storages built specifically for this purpose. However, whole-store fumigations carried out in conventional bag stores modified for this purpose have not always yielded good results (Calverley 1984a).

The technique of whole-store fumigation using phosphine has been applied over a period of years to poorly sealed godowns in Bangladesh and Pakistan. Serious fumigation failures have been reported as a result of the reduced exposure periods to lethal fumigant concentrations resulting from this malpractice (Tyler et al. 1983). The situation has been exacerbated by the development of high levels of phosphine tolerance in a number of stored product pest insects in the Indian region. However, practical strategies have been devised to retain the use of whole-store fumigation in partially sealed storages and also control these resistant strains. In very leaky storages that cannot be sealed to meet even these requirements for gas retention, 'sheet fumigation' of individual bag stacks is recommended (Friendship et al. 1986; Hafiz Ahmed et al. 1986). It is now recognised in some countries that it is impossible to undertake whole-store fumigations in existing storage structures, and that 'sheet fumigation' is the only effective method for disinfesting bag-stacks (Prachak Charoen and Ito 1986).

Similarly, in West Africa, whole-store fumigations of small 'banco' stores, of mud brick and plaster construction are not considered to have been successful (Banks 1986a), even after repairs and sealing in an attempt to render them sufficiently gas-proof (Webley and Harris 1979). Whole-store fumigations of similar small-scale village grain stores, designed and built to be sealed have, however, performed satisfactorily (Harnisch and Krall 1986; Hayward 1984).

Some bulk storages in the tropics are now designed to permit fumigation, and the opportunity that silos offer for efficient and effective fumigation is recognised (Newman 1988; Newman 1990; Shukla and Patil 1989). Operational problems have, in some situations, made fumigation difficult to execute (Umar Khan Balouch and Asim Rahim Kazmi 1988). In some complexes where old concrete silos are in use, considerable gas loss has been observed to occur through their walls (Conway & Mohiuddin 1984). Elsewhere, silos are known to have cracked sufficiently to prevent effective fumigation. Where bunkers have been adopted, disinfestation may be carried out using phosphine (Banks and Sticka 1981) or controlled atmospheres (Jay et al. 1990).

Requirements for Successful Fumigation

Fumigation plays a key role in the control and management of infestation in commodities stored in the tropics. It has proven to be a versatile technique and great reliance has been placed on it to underpin the success of other pest and quality control measures, particularly in countries where admixture of protectants to grains is prohibited. It is used throughout the storage system:

- as an adjunct to storage hygiene to ensure that stocks entering storage are free of infestations;
- as a curative treatment when other physical and chemical pest control measures fail to control infestations; and
- for regulatory purposes to comply with international quarantine or trade requirements.

The increased dependence on fumigation in the tropics since the introduction of phosphine has matched the increasing agricultural use of pesticides evinced in a swing away from traditional pest management techniques towards reliance on routine pesticide application (Putter 1984). Similarly in commodity storage, the increased dependence on fumigation has led to reduced awareness both of alternative infestation control strategies and of fumigants other than phosphine.

Use of substandard fumigation techniques has led to phosphine resistance and is causing concern that further abuse of this fumigant may have a damaging long-term effect on its future availability (Winks 1986b; Bond 1990). The potential for resistant strains to be spread through international trade (Conway 1986), with the concomitant problems of controlling them, may present problems in export markets (Rassman 1988; Reichmuth 1988).

In order to ensure the continued use of fumigation in the tropics, it is essential to establish a target, or standard, for effective fumigations. Effective fumigations are those in which there is a total kill, i.e., no survivors from the original infestation. For practical purposes such fumigations can be defined in terms of the gas concentration attained at the end of the exposure period:

- for phosphine — a minimum exposure period of 7 days ending with a final gas concentration at, or above, 80 ppm (Annis 1990a). *In practice, this may involve a 10-day fumigation.*
- for methyl bromide — in normal commodity fumigations requiring exposures between 24–48 hours carried out at temperatures:
  - between 25°–29°C: a final Ct product of 150 g hours/m^3
  - at or above 30°C: a final Ct product of 100 g hours/m^3 (AFHB/ACIAR 1989)
- for carbon dioxide — a minimum exposure period of 15 days, ending with a final gas concentration at, or above, 35% (Annis 1990b).

Prevention of resistance is an integral consideration in the continued use of fumigation in the tropics (Winks 1980), particularly as the prospects for developing new fumigants appear very poor (Banks 1987). Choice of fumigant is not limited to methyl bromide and phosphine. Both carbon dioxide (Jay 1986) and hydrogen cyanide (Banks 1987) are available, and the technology for their use well established. They should both be brought into service, along with methyl bromide, phosphine and the formates (Banks 1987), so that their advantages may be used in alternation within storage systems as a tactic to prevent fumigant resistance (Roush 1989). Another tactic involves an extension of the requirements for effective fumigation, demanding high standards of gastightness and increased exposure periods, to control strains of insects resistant to phosphine (Winks 1986b).

Bag-stacks can be enclosed to the standards of gastightness required for effective fumigation using the sealed stack system (Annis 1990b), which at the same time provides long-term protection against reinfestation. This system, which can be sealed to the stringent requirements for disinfestation with carbon dioxide, has also been used for phosphine fumigation and can extend exposure periods for this fumigant (Annis 1990b). An added operational feature of the technique is the pressure test. This provides an accurate, practical means of predicting the outcome of a fumigation, something which remains impossible with sheet fumigation.

Effective 'sheet fumigation' of bag-stacked commodities with methyl bromide and phosphine is possible indoors, provided all measures to prevent gas loss are taken. Leakage downwards can be avoided by routinely building bag stacks on gas-proof floor sheets. Techniques for sheeting and sealing bag-stacks (Anon 1974; Stout 1983) should be rigorously implemented. Particular attention is required where sheets must be joined, for which timber laths and carpenters' 'C' clamps provide a more effective seal than rolling and clipping. When a floor sheet is used, the seal at floor level is greatly improved when this is folded over with the cover sheet and weighted down.

Loose sand, or sand snakes, are the preferred means of sealing at floor level. Where sand snakes are used, these should not be filled to more than two-thirds of their capacity, so that they can lie flat filling any depressions in the floor to make the best possible seal. Care must be taken to ensure that sand snakes are placed closely side-by-side and flattened so no gas loss can occur through gaps that might be left between them. Chains and timber baulks should not be used as these do not provide an effective seal, and can cause extensive damage to fumigation sheets.

The seal produced by these methods must be judged as inadequate by modern standards, as gas losses from enclosures of this type can still be substantial (Banks 1986b). However, gas loss can be significantly reduced by checking for, and sealing leaks, a practice that has largely fallen into disuse with the widespread adoption of phosphine. For methyl bromide fumigations, halide detector lamps continue to provide an effective means for this purpose (Bond 1984), though a more reliable and safer electronic instrument (Riken) is now available. For phosphine fumigations, detector tubes provide a simple means for leak detection although electronic detectors are becoming available (Ducom and Bourges 1986).

Torn or holed fumigation sheets should be promptly repaired and maintained in a gas-proof state. Fumigation sheets made of PVC can be very effectively patched using glue made from PVC dissolved in methyl ethyl ketone*. This makes a strong permanent and flexible bond (Banks 1986b), surpassing the patching usually carried out with other glues or self-adhesive insulating tapes.

The practice of using two 'leaky' sheets, one on top of the other to obtain a gas proof enclosure, should be avoided, as significant gas loss will still occur. There is the additional risk that insects finding harbourage between the sheets will survive and subsequently reinfest the commodity, with the likelihood of resistance developing.

Almost complete gas loss can occur very rapidly where sheeted stacks are exposed to wind, and every step should be taken to reduce its effects in a storage where sheet fumigation is being carried out. Stacks built outdoors are particularly at risk in this respect (Banks 1986b). In situations where excessive gas loss occurs and fumigant concentrations fall below expected values, top-up doses can be added to ensure that the correct final level is obtained (Annis 1990b; Stout 1983). Thus, to ensure the successful outcome of a sheet fumigation, it is essential that fumigant concentrations are monitored at intervals during the exposure period, and finally when it is terminated. To do this effectively, fumigators must be provided with the appropriate equipment and materials.

Effective sheet fumigation on a routine basis should always be possible — given the basic requirements for success: management awareness of the need for fumigation; good, well

* In the People's Republic of China a glue consisting of dichloroethane and perchloroethane (4:1) is used to patch PVC sheets (Wang Han Bin & Tang Zhenjia 1986a.

maintained equipment; and well-trained fumigators. With these requirements assured, then a combination of careful attention to detail and common sense should ensure the successful outcome of a fumigation.

Alternative Fumigation Techniques

Effective fumigation requires a gastight enclosure, which in bag storage is most commonly provided by temporarily enclosing bag-stacks under gas-proof sheeting whilst in storage. Alternative techniques, large- and small-scale, have been developed to permit the use of controlled atmospheres. These also offer protection against reinfestation. Elsewhere in the storage system, practical opportunities to make use of gas-tight enclosures have been recognised and applied.

Bag Storage in Sealed Plastic Enclosures

This technique is compatible with existing bag storage practices and makes few extra demands of them. It provides a method for long-term storage that has the advantages of improving the efficacy of fumigation, reducing fumigant use and at the same time protecting stacks from reinfestation. It eliminates the penalty of repeated spray applications and fumigations, and the possibility of residue accumulation (Ong 1985; Anon 1986; Anon 1988b; Hayward 1984) normally associated with long-term storage. It also has strategic value by providing the means for using an 'alternative' fumigant, i.e. carbon dioxide, when the need arises: for example, either when there is a requirement for a residue-free treatment, or to eliminate fumigant resistant insect strains. Furthermore it can be integrated into existing commodity management systems (Annis and van S. Graver 1987).

In Australia, the technique has been adopted for storing groundnut seed, providing protection against infestation and moisture uptake (M. Read, pers. comm.) and in Indonesia it is used by BULOG as one of a range of storage options (Conway et al. 1990; Yun C. Nataredja and Hodges 1990). In the People's Republic of China, PVC membranes are likewise used with controlled or hermetic atmospheres to store rice (Wang Han Bin and Tang Zhenjia 1986a); while in Pakistan a simple sealed polyethylene enclosure has been used with phosphine for long-term storage of wheat (Hafiz Ahmed et al. 1986). A variation of the standard sheet fumigation technique, using multiple applications of hydrogen cyanide to 'permanently' sheeted stacks, has been applied for long-term storage of bag-stacked polished rice in the United States of America (Tilton 1961). On a smaller scale, Volcani Cubes can also be used for indoor storage (Navarro and Donahaye 1990).

Whole-Store Fumigation

This technique has a number of advantages: it is simpler than sheet fumigation, particularly where stores can be sealed; it maximises the space available in a bag-storage by permitting an increase in stack size and allows stacks to be built around obstructions that otherwise prevent sheet fumigation; it eliminates the expense of gas-proof sheeting; and, in well-sealed stores, it prevents reinfestation. In well-sealed (Banks and Annis 1980), or purpose-built storages the technique has performed well (Green 1987), but it is not recommended for storages that cannot be sealed. In situations where there is no alternative means of disinfestation and the technique must be implemented, it is essential that insects are exposed to lethal levels of fumigant throughout the required exposure period. This may be achieved by a multiple-dosing treatment that accepts a degree of gas loss from these poorly sealed storages and compensates for it by the addition of extra fumigant at two- to three-day intervals (Friendship et al. 1986; Wang Han Bin and Tang Zhenjia 1986b).

Hermetic Storages

When dry, lightly infested grain is hermetically stored, infestation control may be a lengthy process. Under such circumstances very small doses of fumigant have been used to hasten the rate of insect control achieved by oxygen depletion (de Lima 1984). Similar results can be obtained with bagged grain stored in flexible silos (Kenneford and O'Dowd 1981).

In-Transit Fumigation

Barges, lighters and ocean-going vessels have been used as fumigation enclosures (Bond 1990; Davis 1986; Prachak Charoen and Ito 1986). Despite concern about the safety aspects of the technique (Snelson and Winks 1981), in-transit fumigation continues to be practiced. In Thailand, a recirculatory system for in-transit fumigation of grain with phosphine, as described by Leesch et al. (1986), is currently used for grain exported in bulk carriers (R.P. Sririrak, pers. comm.). Recent developments in fumigation technology (Winks 1990) may find application to greatly improve the safety aspects and efficacy of in-transit shipboard fumigations.

Carbon-dioxide-rich controlled atmospheres have been applied for in-transit disinfestation of commodities in barges (Jay et al. 1990) and in standard ISO shipping containers (Banks 1988). In Australia the technique is used to export groundnuts to Japan and New Zealand with considerable cost savings over the standard fumigation treatment. Controlled atmospheres have also been used to disinfest commodities in LASH barges (Banks 1979) and bulk carriers (Adamovsky and Mordkovich 1989).

Bag Liners

Polyethylene bags placed as liners inside woven jute or polypropylene bags provide a gastight enclosure, making it possible to fumigate the contents of individual bags and also providing a physical barrier against reinfestation (Proctor and Ashman 1972). Groundnuts have been stored safely in such lined bags without moisture migration for up to three months. The system has application for a number of commodities, particularly those of high value, e.g. well-dried cocoa (Prado et al. 1988). Similarly, 'Joseph Sacks' (Anon 1988c) made of sealable laminated plastic can be used for this purpose.

Fumigation Tents

There is frequently a need to undertake small-scale fumigations for which sheets, on account of their size, are inappropriate. Portable fumigation enclosures, such as the the Rentokil Bubble (Smith 1990) and the Volcani Cube (Navarro and Donahaye 1990), are effective for this purpose.

An application in storage practice is disinfestation of used bags, pallets, and spillage recovered during the course of storage hygiene. All provide a source of reinfestation that is frequently overlooked.

Alternatives to Fumigation

The relative ease with which fumigation can now be undertaken has in many places led to a reduced awareness of the alternatives. The need to delay the development of fumigant resistance by avoiding unnecessary fumigant use, combined with concern about residues in commodities exported from the tropics (Anon 1986; Anon 1988b; Hayward 1984), make it important to recognise and utilise alternatives to fumigation.

Hygiene

A well-managed program of storage hygiene can do much to reduce infestation levels using the simplest of tools — the brush and the shovel. Storage hygiene provides the foundation for the success of all other infestation control procedures because it reduces the possibility of uninfested commodities being infested 1. by contact with other infested commodity or 2. by migration of insect pests. Hygiene should be rigorously monitored by regular inspection and effective stock control. Lack of hygiene can result in strong selection for resistance caused by reinfestation leading to the necessity for repeated refumigation at short intervals.

Storage hygiene is pivotal to the implementation of integrated commodity management. Inspection, as commodities are first taken into a storage, provides the basic information upon which action thresholds and infestation control options are selected: grain variety, moisture content, presence or absence of infestation, dockage, degree of processing, end use, value and duration of storage. With these factors established and constantly monitored, control options can be selected, timed for maximum efficiency and changed to suit circumstances.

Stock control based on the principle of first-in/first-out can, on its own, be a very effective infestation control method. In Papua New Guinea, bagged rice is largely imported from Australia. The organisation handling the supply and distribution of this commodity has, by means of very efficient stock control, virtually eliminated the need for fumigation from its operations and is still able to deliver a high quality product to the market. A key component of this strategy has been maintenance of rigorously high standards of hygiene from source of supply to wholesale outlet.

Drying

The most important factor determining the storability of a commodity in the tropics is its moisture content. Drying is not only the best preventive measure to counter infestation but also a good control measure. The moisture content of a commodity also affects other control measures: thus the biological activity of protectant insecticides may be affected by commodity moisture content (Samson and Parker 1986) and, in varieties of cowpeas resistant to insect infestation, it has been shown that resistance decreases as moisture content increases (Anon 1988d).

Provided bag-stacks are built on pallets, natural ventilation will remove a considerable amount of moisture. Various drying processes involving special stacking procedures are well known. Nevertheless, neither these nor traditional sun drying methods are sufficiently reliable, or convenient, to handle wet-season grain harvests (Acasio 1982). Using existing mechanical drying facilities, effective strategies have been developed to rapidly dry such grain to levels at which they can be safely stored (Adamczak et al. 1987; Driscoll 1987).

Hermetic Storage and Controlled Atmospheres

Large-scale hermetic stores provide a low energy means for long-term pesticide-free storage of bulk grain. Operational losses have been lower than those normally encountered in conventional bag storage (de Lima 1980a). Effective stock rotation is possible by integrating the operations of a bag-storage with those of a hermetic storage system (de Lima 1980b).

Controlled atmospheres provide a very effective means of storing commodities to provide a residue-free product acceptable to overseas markets and discriminating domestic markets in the tropics. Controlled atmospheres have application both in bag and bulk storage. In West Africa, controlled atmospheres are in use for bulk storage of cocoa, coffee, and paddy in silos (H.J. Banks, pers. comm.).

Despite the more stringent technical and management requirements for this form of storage (Calverley 1984b), it is being adopted for bag storage in the tropics (Samarasinghe et al. 1987). These storages, being well-sealed, may also be used with conventional fumigants, thereby allowing alternation of fumigants, and can meet the fumigation requirements of differing commodities.

Controlled atmospheres have applications on a smaller scale. In India, cashew nuts are packed in controlled atmospheres contained in airtight 20 L tins. This application ensures that the commodity is infestation free, and prevents quality deterioration while providing a robust container suitable for export trade.

Insecticides

For bagged commodities prophylactic use of grain protectant insecticides (Bengston 1986) is commonly the only practical alternative to fumigation. They may be applied as fabric treatments, space sprays or to the bag-stack as surface sprays (Webley 1986a,b). Such treatments will reduce, but not eliminate infestations and it is essential to combine them with rigorous hygiene measures to keep insect numbers low. In the Sahel, long-term protection of bagged grain has been achieved by covering stacks with insecticide-impregnated cotton sheets. This technique has reduced insecticide usage to about 25% of that required for conventional treatments (Hayward 1984).

Insecticides are relatively cheap and recent work has established application rates for admixture that are applicable to the moisture contents at which grains are stored in the tropics (Bengston 1988; Samson and Parker 1989; Samson et al. 1988). In bulk storage situations, the option to admix protectants is available as a first treatment that can be integrated with fumigation or use of controlled atmospheres where sealed storages are available. In bag storage systems, the option of admixing protectants is restricted to the time when a commodity is first bagged, as failure can result if protectants are admixed when infestation levels are high. A method to integrate insecticide admixture and sealed storage of bagged commodities has been proposed as a means to extend the use of bag storage (Annis and van S. Graver 1987).

Processing

A commodity's storability can be altered by processing it. Some commodities in their raw state are more resistant to infestation, or less susceptible to change in quality. However, this advantage is gained at the expense of an increased requirement for storage space, thus:

coffee may be stored in parchment, which is less likely to suffer change in quality — an advantage in remote areas where transport is unreliable; groundnuts may be stored in-pod with protection against most of the insects that attack unprotected groundnut kernels; and rice may be stored as paddy (Haines 1982a).

In general, the products of milling a commodity, e.g. grits, flour, etc. are more susceptible to infestation. An exception is rice: well polished, milled rice, as a whole grain, is less susceptible to infestation (McFarlane 1978).

No Control Implemented

The option to exercise no control methods (other than hygiene) may be selected with a knowledge of the end use of a commodity, the desired quality standard, remaining duration of storage and the potential for cross infestation. Thus, some commodities can be disinfested during further processing, e.g. paddy to polished or parboiled rice, or whole grains to flour, or where established levels of infestation may be acceptable for stock feeds. Similarly, in situations where the expected duration of storage is short, no control measures may be deemed necessary. In some circumstances, natural occurrences of predatory insects may effect adequate control that may be recognised and utilised.

Absence of infestation control may be enforced by market prices that make it uneconomic. In the South Pacific islands, for example, copra may be stored unprotected for long periods, during which time it becomes heavily infested and presents a major source of infestation for both imported and exported commodities.

Conclusion

There has been a tendency in most postharvest systems towards major dependence on a small number of disinfestation procedures (Haines 1982b). In this respect, extensive reliance has been placed on fumigation following the introduction and widespread adoption of phosphine. The development of resistance to this fumigant (Champ and Dyte 1976; Tyler et al. 1983) has, however, led to concern about its continued availability (GASGA 1986).It has therefore become important to ensure that fumigation is used to maximum effect, in order to prevent the spread of resistance in the tropics and preserve its key role in commodity storage.

Integration of fumigation into a commodity management system (Evans and van S.Graver 1987) is based on applying knowledge of the interactions (de Lima 1987; Heselhurst et al. 1987) that affect the manner by which a commodity is stored. Application of this information will differ from storage to storage within a system, from commodity to commodity and according to end-use. At the national level, there can be interaction between different commodity storage systems, which may be complicated when high- and low-value commodities, with conflicting infestation control standards, are produced as part of the same farming system, e.g., cocoa and copra. Many commodities grown and stored in the tropics are exported, and further interactions at the international trade level must be taken into consideration when formulating infestation control programs.

The development of practical techniques for applying controlled atmospheres to bagged commodities provides an alternate gaseous disinfestation technique which, combined with higher standards of gastightness, offers a means for continued and efficient use of conventional fumigants. Opportunities to make effective use of fumigants and controlled atmospheres within commodity storage systems must be recognised and utilised.

Alternate control measures, or actions to supplement the efficiency of gaseous treatments, should be utilised particularly where they offer greater chances of success. These may even involve management decisions to relocate and centralise storages to maximise the impact of climate, logistics, etc. on infestation control measures (McFarlane 1988).

Adoption of good fumigation practice is dependent on the relevant technology being available so that it can be used effectively. Government policy, in the form of regulations to enforce quality standards in commodity exports or plant quarantine criteria on imports, is an incentive towards the goal of good fumigation practice (Horrigan 1987). Enforcement of both domestic and international regulations can improve fumigation practice to ensure their successful outcome.

In the ASEAN region, action has been taken to develop a workable code of practice for fumigation (AFHB/ACIAR 1989), aimed at ensuring that all fumigations carried out within the region attain at least a minimum standard for success — a complete kill of all insects present. Implementation of the code throughout the region is intended to prevent the development and spread of resistance and may permit fumigators to refuse to carry out fumigations under substandard conditions. For successful implementation, such a code must be supported by enforceable legislation to ensure management awareness and cooperation, and registration of trained fumigators. For example, domestic phytosanitary regulations may be invoked to prevent the spread of pests through domestic and international trade, e.g. The Plant Protection – Control of *Prostephanus truncatus* Rules 1986 in Tanzania (McFarlane 1988).

International regulations can also affect the conduct of fumigation in the tropics. Some countries that import commodities enforce strict domestic quarantine regulations requiring all infestable imported goods to be fumigated to specified standards before export. Failure to comply with these standards can involve costly refumigation at the ports of destination. International fumigation contractors are now responding to these problems by enforcing high standards in their overseas operations (Bert Prinsen, pers. comm.). Concern about the problems that might be caused by the introduction of fumigant-resistant strains of insects on imported commodities has prompted calls for stricter implementation of quarantine regulations in some European countries (Rassman 1988; Reichmuth 1988).

The successful outcome of a fumigation is dependent upon the knowledge and skill of the personnel undertaking this work. Fumigation should be carried out only by well-trained fumigators who are fully aware of its objectives — and any impediments to its successful outcome. Training should be relevant to the practical applications of fumigation and involve the transfer of as much 'proven experience' as possible.

The lessons of training must be supported by regular supervision to ensure that the standards required for effective fumigations are maintained.

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