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REVIEW

Alternative domestic rodent pest management approaches to address the hazardous use of metal phosphides in low- and middle-income countries

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Abstract

Metal phosphides, particularly aluminium phosphide (AlP) and zinc phosphide (Zn_3P_2), are widely used in low- and middle-income countries (LMICs) as rodenticides in urban and domestic environments due to their low cost and high toxicity to rodent pests. However, they are also highly toxic to humans with no antidote available and have been associated with numerous fatal cases of intentional and accidental poisoning. This paper reviews alternatives to metal phosphide use for rodent pest management in urban and domestic environments, highlights case studies of effective alternative approaches, and provides recommendations for research and policy. This review identifies numerous alternative methods available for managing rodent pests in domestic/urban settings that can replace metal phosphides. These include chemical methods, i.e. rodenticides, and non-chemical methods, e.g. rodent-proofing, sanitation and trapping. However**,** because the majority of chemical rodenticides qualify as highly hazardous pesticides due to acute human health toxicity, environmental toxicity, and/or bioaccumulation, simply selecting substitute chemical rodenticides to replace metal phosphides are likely to replace one set of hazards with others. Thus, careful risk and hazard assessments are needed when considering substituting with other chemicals. Overall, we need to move away from current levels of rodenticide reliance towards more integrated and ecologically based approaches.

Keywords Ecologically based rodent management · Highly hazardous pesticides · Integrated pest management · Pesticide poisoning · Pesticide regulation · Urban policy

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Introduction

The metal phosphides, aluminium phosphide (AlP), zinc phosphide (Zn_3P_2; herein referred to as ZnP) and to a lesser extent, magnesium phosphide (Mg_3P_2; herein referred to as MgP), are widely used as fumigants for stored products and as rodenticides due to their low cost, wide availability and high toxicity to a broad range of insect and rodent pests (Bumbrah et al. 2012; Marashi 2015; Trakulsrichai et al. 2017; UNEP et al. 1988). However, metal phosphides are highly toxic to humans and other vertebrates (UNEP et al. 1988). Due to their high toxicity, rapid onset of systemic symptoms (with high risk of mortality within 24 h) and lack of specific antidote, the case fatality is as high as 67% for AlP and 25% for ZnP (Chugh et al. 1998; Gunnell et al. 2017; Shadnia et al. 2010). Thus, metal phosphides have been associated with numerous fatal cases of intentional and accidental poisoning, with cases reported across the world, especially in low- and middle-income countries (LMICs) (Anand et al. 2011; Bhandari and Basnet 2022; Proudfoot 2009; Yogendranathan et al. 2017). For example, in Pakistan, Iran and Nepal, AlP is reported as one of the most frequent agents for fatal self-poisoning (Etemadi-Aleagha et al. 2015; Ghimire et al. 2022). In Zimbabwe, AlP is one of the most common causes of pesticide poisoning, recently causing the death of three children after it was applied to stored maize (NAFDAC 2022). In Thailand, India, and Nepal, ZnP is a common self-poisoning agent as well as frequently involved in accidental poisonings, including young children (Ghimire et al. 2022; Peshin et al. 2014; Trakulsrichai et al. 2017; Varghese and Erickson 2022). In Tanzania, a survey conducted in 2006 revealed that ZnP was one of the most common poisoning agents of children under 18 years old (Lekei et al. 2017).

Metal phosphides are available in a range of formulations designed for different uses. These formulations include solid tablets (3 g or 12 g of 56% AlP), pellets, compressed discs, bag blankets, paste or powder—the last of which is commonly sold in sachets (Murali et al. 2009; Proudfoot 2009; UNEP et al. 1988). Uses include phytosanitary treatment of food and non-food products for import/export, commercial/large-scale insect pest control for stored food products, smallholder grain storage insect pest control, domestic/peri-domestic rodent pest control in and around houses (including grain stores), and agricultural rodent pest control (Buckle 1994; Bumbrah et al. 2012; Nayak et al. 2020).

AlP and MgP are unstable solids used as a fumigant via the release of phosphine gas (PH_3) (Marashi 2015; Proudfoot 2009). Phosphine gas is released when AlP or MgP comes into contact with atmospheric moisture, as well as water and other neutral or acid pH liquids. However, phosphine release is even more vigorous after contact with an acid, such as hydrochloric acid in the stomach (i.e. gastric acid) (Knight 2013; Proudfoot 2009). When used for rodent pest management, either pellets or tablets are applied to rodent burrows which are subsequently closed up with soil with the aim to gas the rodents (Buckle 1994).

ZnP is a relatively stable compound that can be applied as a bait; thus, it is more commonly used for rodent pest management than AlP and MgP (Marashi 2015). In addition, ZnP requires a sufficiently acid pH environment for hydrolysis to occur, releasing phosphine gas upon contact with acids such as gastric acid (Knight 2013; Trakulsrichai et al. 2017). When used against rodent pests, ZnP is typically applied in baits at concentrations of 2%, but concentrations can vary, ranging from 1 to 5% (Buckle 1994; UNEP et al. 1988). In many LMICs, 80% wettable powder formulations are commonly available as a low-cost pre-mix for bait preparation by the user (e.g. Bhandari and Basnet 2022; Buckle 1999; Stuart, A., pers. obs.; CIBRIC 2023; FPA 2023; PPD 2022).

Metal phosphides pose a high risk to human health. Routes of entry into the body include via ingestion and via inhalation of the highly toxic phosphine gas, which is denser than air and can thus travel short distances, e.g. to adjacent buildings (Proudfoot 2009; Yogendranathan et al. 2017). When ingested, metal phosphides are hydrolysed by gastric acid into phosphine, which is absorbed into the bloodstream. Phosphine is a respiratory toxin that inhibits many enzymatic systems, such as cytochrome C oxidase and oxidative respiration, which can result in renal failure and liver failure (Yogendranathan et al. 2017). Other severe clinical symptoms of phosphine poisoning include circulatory collapse, hypotension, pulmonary oedema, congestive heart failure and cardiac arrhythmia (Trakulsrichai et al. 2017). The main uses of concern to human health include i) when metal phosphides are used as a fumigants in or near to human habitation—which can lead to accidental poisoning from phosphine gas to bystanders/ adjacent buildings, ii) occupational exposure to phosphine gas in stores, warehouses or during transport, and iii) when solid formulations are easily accessible during use or when being stored or sold for later use (either against insect or rodent pests)—which can lead to intentional or unintentional poisoning via ingestion (Proudfoot 2009).

To address such risks to human health, many countries have banned, withdrawn or restricted the use of metal phosphides (CILSS 2022; Etemadi-Aleagha et al. 2015; Karunarathne et al. 2021; PAN 2022). For example, ZnP has been banned/withdrawn in at least seven countries and the US Environmental Protection Agency (EPA) only permits consumer products of ZnP and other rodenticides to be sold as block or paste poison bait, with loose bait forms (e.g. pellets, grains, powders) no longer permitted (EPA 2023). Recently, the US EPA also issued a proposed interim decision to classify ZnP as a "restricted use pesticide" that can only be applied by certified pesticide applicators (EPA 2022). In West Africa and several other countries, AlP, MgP and ZnP are already classified as "restricted use pesticides" (CILSS 2022). In addition, many private voluntary standards (PVS, also known as voluntary sustainability standards) in certified food and fibre supply chains and retailer companies have included AlP and ZnP in their prohibited chemical lists (IPMcoalition 2023).

Despite their hazards, metal phosphides remain widely available and/or are largely unregulated in many LMICs due to lack of bans and restrictions or due to lack of enforcement. To support a transition away from metal phosphides, it is important that regulators, policymakers, the supply chain sector and users are aware of the alternatives (Stuart et al. 2023). To address this knowledge gap, we reviewed available information on alternatives to metal phosphide use for rodent pest management, identify further research needs and make recommendations for decision makers. In addition, we provide two case studies demonstrating less hazardous alternative approaches in LMICs that are at least as effective in reducing rodents as metal phosphides. Defining a universally acceptable threshold or tolerance limit for effective or successful rodent pest management is challenging due to location-specific factors. However, the primary goal of any rodent control intervention is to reduce rodent infestation and its causative factors to a level that no longer adversely affects the community (CDC 2006). Metal phosphide-based interventions typically yield short-term rodent population reductions of 30–90%, and control levels of around 70% are somewhat considered effective (Eisemann et al. 2003). Reviews on alternatives for agricultural rodent pest management are comprehensively covered in the literature (e.g. Brown et al. 2017; Buckle and Smith 2015; Singleton et al. 2021; Swanepoel et al. 2017). In this paper, by contrast, we focus on alternative rodent pest management approaches for domestic/urban environments (from household to municipal scale) where risks of human exposure to metal phosphides are greatest (Md Meftaul et al. 2020).

Alternatives to metal phosphides for domestic rodent pest management

There are a number of chemical and non-chemical tools and methods available that can be used as a direct alternative to metal phosphide rodenticides or as part of an integrated approach to replace their use in urban and domestic settings. These are described in the following section. However, it should be emphasised that all chemical approaches to rodent control may present a risk to human and environmental health. They usually only provide short-term fixes (Lee et al. 2022), while potentially accumulating long-term problems due to the spread of behavioural or genetic resistance for some compounds (Colvin and Jackson 1999). Sustainable rodent pest management is generally best achieved if a variety of methods are employed (Witmer 2019).

Chemical rodent pest management methods

The chemical rodenticides used to manage rodent pests are numerous and can be grouped into three main categories: 1) acute (fast-acting) rodenticides, 2) first generation anticoagulants (FGARs) and 3) second generation anticoagulants (SGARs).

Acute rodenticides

Acute rodenticides include AlP, MgP and ZnP, as well as alpha-chloralose, alpha-chlorohydrin, carbon dioxide, bromethalin, cholecalciferol (vitamin D3), norbormide, sodium monofluoroacetate (compound 1080), strychnine and yellow phosphorus (Erickson and Urban 2004; Isackson and Irizarry 2023; Jacob and Buckle 2018). Alpha-chloralose kills via hypothermia and is considered to be mostly effective against house mice (*Mus musculus*) at temperatures below 15 °C (Meehan 1984; UFAW 2021). However, it is also highly toxic to birds and aquatic organisms and moderately toxic to mammals, including humans (Table 1; Lewis et al. 2016). Alpha-chlorohydrin is a toxicant sterilant which can cause sterility after a single dose and is highly toxic to birds (Ericsson 1982; Lewis et al. 2016). Carbon dioxide causes asphyxiation by hypoxia. It binds to haemoglobin, which prevents the uptake of oxygen leading to death within minutes (Permentier et al. 2017). For rodent management, carbon dioxide was recently registered in the United States as a solidified dry ice pellet form that should be placed in rodent burrow entrances (DC_Health 2018). Cholecalciferol, the biologically active form of vitamin D, is completely non-toxic in small amounts, but massive single doses or prolonged low-level exposure causes hypercalcemia in rodents leading to death in 3–4 days (Klemann et al. 2023). Bromethalin is a neurotoxic diphenylamine that poisons the central nervous system that ultimately causes respiratory arrest (Hygnstrom et al. 1994). Norbormide is largely *Rattus* species-specific and causes extreme and irreversible vasoconstriction that results in rapid death (Hayes and Laws 1991). To overcome sub-lethal effects and consequent bait shyness, promising prodrug forms of norbormide have been developed to delay the action of the rodenticide and improve palatability (Campbell et al. 2015). Sodium monofluoroacetate (compound 1080) inhibits several metabolic processes, leading to seizures and shock (Cottral et al. 1947). Strychnine acts as an antagonist of glycine receptors and generates uncontrollable muscle spasms (Isackson and Irizarry 2023; Sherley 2004). As with the metal phosphides, the symptoms

Table 1 Hazard profile of acute and anticoagulant rodenticides (Source: Erickson and Urban 2004; Lewis et al. 2016; PAN 2021). Obsolete rodenticides are excluded. Y = yes

Active ingredient	Mammals—Acute oral LD_{50} (mg kg^{-1})[a]	Birds—Acute oral toxicity	Bio-concentration factor	PPDB assessment on human health			WHO Classification[b]	Fatal if inhaled (H330)[c]	GHS^{+} repro (1A,1B)[d]	WHO/ FAO HHP criteria met[e]	PAN HHP list[f]
Acute rodenticides											
Alpha-chloralose/ chloralose	400	High	Low risk	Moderately toxic	Very hazardous if ingested	Narcotic	II				
Alpha-chlorohydrin	131	High	–	Moderately toxic	May cause pulmonary haemorrhaging & congestion	Kidney and liver toxicant	1b	Y		Y	Y
Aluminium phosphide	8.7	High	–	Highly toxic	May cause dermatitis	Heart and lung toxicant	FM	Y		Y	Y
Bromethalin	2	High	–	Highly toxic	Both acute and chronic effects can occur following ingestion	CNS toxin	1a	Y		Y	Y
Sodium fluoroacetate (1080)	1.2	High	–	Highly toxic	CNS effects include tremulousness, hallucinations, convulsions, and respiratory depression	Possible thyroid and kidney toxicant	1a	Y		Y	Y
Carbon dioxide (dry ice)	100,000*	–	Low risk	Harmful by inhalation	Chronic exposure can produce adaptation as well as producing metabolic acidosis		Not listed				
Strychnine	16	Mod	–	Highly toxic	CNS and cardiovascular toxicant	Convulsant	1b			Y	Y
Cholecalciferol (Vit. D3)	1426	Low-mod	Low potential	Very toxic					Y	Y	Y
Zinc phosphide	12	High	–	Highly toxic	May be fatal if swallowed		1b			Y	Y

Table 1 (continued)

Active ingredient	Mammals—Acute oral LD_{50} (mg kg^{-1})[a]	Birds—Acute oral toxicity	Bio-concentration factor	PPDB assessment on human health			WHO Classification[b]	Fatal if inhaled (H330)[c]	GHS^{+} repro (1A,1B)[d]	WHO/ FAO HHP criteria met[e]	PAN HHP list[f]
Magnesium phosphide	10.4	High	–	Moderately toxic		FM	Y		Y	Y	
Norbormide	> 52.0	Mod	–	Harmful if swallowed			O				
First generation anticoagulants											
Chlorophacinone	3.15	High	Low risk	Highly toxic	Causes internal haemorrhages	Suspected cardiovascular toxicant	1a			Y	Y
Coumatetralyl	16.5	Mod	Threshold for concern	Highly toxic	May cause haemorrhaging	1b		Y	Y	Y	
Diphacinone	2.3	Low-mod	–	Highly toxic			1a			Y	Y
Pindone	280	Mod	–	–		O			Y		
Warfarin	10.4	Low-mod	Low risk	Highly toxic	Causes internal haemorrhages	May be absorbed through the skin and cause systemic poisoning	1b	Y	Y	Y	Y
Second generation anticoagulants											
Brodifacoum	0.4	High	High potential	Highly toxic	Severe poisonings may lead to massive haemorrhaging		1a	Y	Y	Y	Y
Bromadiolone	> 0.56	Mod	Threshold for concern	Very toxic	May cause haemorrhaging	Slight eye irritant	1a	Y	Y	Y	Y
Difenacoum	1.8	High	High potential	Highly toxic	May cause haemorrhaging	Vapour may cause dizziness or suffocation	1a	Y		Y	Y

Table 1 (continued)

Active ingredient	Mammals—Acute oral LD_{50} (mg kg^{-1})[a]	Birds—Acute oral toxicity	Bio-concentration factor	PPDB assessment on human health		WHO Classification[b]	Fatal if inhaled (H330)[c]	GHS+ repro (1A,1B)[d]	WHO/ FAO HHP criteria met[e]	PAN HHP list[f]
Difethialone	0.56	High	High potential	Highly toxic	May cause haemorrhaging	1a	Y	Y	Y	Y
Flocoumafen	0.25	Mod	Threshold for concern	Highly toxic	May cause haemorrhaging	1a	Y	Y	Y	Y

[a] Based on *Rattus norvegicus*—the preferred test species for evaluation of acute toxicity by the oral and inhalation routes. The rat is usually considered to be a good model for human effects (ECHA, 2017)

[b] According to World Health Organisation (WHO): 1a = extremely hazardous, 1b = highly hazardous, II = moderately hazardous, O = obsolete, FM = fumigant (The solid form of aluminium phosphide is classified by WHO as 'Fatal if swallowed')

[c] H330 'Fatal if inhaled', hazard classification according to the EU or Japan Globally Harmonised System (GHS). Phosphine (produced by Aluminium and Magnesium phosphides) is classified as H330

[d] Known or presumed human reproductive toxicant according to EU or Japan GHS

[e] According to WHO/ Food and Agriculture Organisation (FAO) criteria for highly hazardous pesticides

[f] According to Pesticide Action Network International (PAN) list of highly hazardous pesticides

*LC50 inhalation value

of yellow (elemental) phosphorus poisoning include multiple organ failure and has been associated with a high number of fatal human poisonings in India (Jeyapal and Sagar 2020; Soni et al. 2020).

These acute rodenticidal compounds vary considerably in mammalian toxicity (Table 1), and their registration status varies among countries. With the exception of norbormide, that is reportedly a selective *Rattus*-specific toxicant (Roszkowski 1965), these acute compounds are not genus or species-specific and, depending on dose and susceptibility, can harm non-target species via primary exposure if they consume bait directly or inhale the gases produced (Shore and Coeurdassier 2018). Rodenticides should thus be placed in tunnels or within secure and purpose-made bait boxes to reduce non-target risk. However—as with placing traps in covers—bait boxes can reduce their efficacy against some species (Buckle and Prescott 2010). For example, Brown rats (*Rattus norvegicus*) are known to be neophobic (i.e. fear of new objects) and it may take days or weeks for a brown rat to enter a bait box. Careful assessment of the infestation, pre-baiting to reduce neophobia, and appropriate placement of bait are recommended. It is essential that measures are taken to minimise human contact and protect non-target species.

Due to the rapid action of acute rodenticides, most, except for bromethalin, have a low risk of bioaccumulation; thus, secondary exposure of non-target species (from consumption of poisoned rodents) is usually not an issue (Table 2). In addition, genetic resistance is unlikely to develop among target species (Erickson and Urban 2004). However, those with moderate to high mammalian toxicity can also pose a significant health risk to humans and caution should be applied when considering these as substitutes for metal phosphides (Table 1). In addition, even though alpha-chloralose is considered to have a low risk to humans and non-target animals when applied correctly and indoors (CRRU 2021), a recent study of human pesticide poisoning cases in Morocco revealed that 33% of the investigated pesticide poisoning cases were due to alpha-chloralose poisoning (Bourekkadi et al. 2021; Dalecky et al. 2023).

First generation anticoagulants (FGARs)

Anticoagulant rodenticides (AR) are delayed acting rodenticides that are toxic to all warm-blooded organisms and are classified as WHO Class Ib and thus meet the FAO/WHO defined criteria for Highly Hazardous Pesticides (HHPs) (FAO and WHO 2016). All anticoagulant rodenticides inhibit vitamin K(1)-2,3 epoxide reductase hampering the synthesis of vitamin K and the clotting factor cascade (Berny 2011). Therefore, the term "anti-vitamin-K" (AVK) compounds is sometimes used. Through their action, blood clotting is greatly reduced and rodents die because of excessive internal and external bleeding. However, in the case of human or accidental animal exposure to an anticoagulant, vitamin K can be administered as an antidote if medical treatment is provided in time (Witmer 2019).

FGARs include chlorophacinone, coumatetralyl, diphacinone, pindone and warfarin (Buckle 1994). These compounds are less toxic, less persistent and less bioaccumulative than SGARs and require the uptake of multiple doses to be effective. However, they are not free from risk to humans and non-target wildlife, especially because larger quantities of these baits need to be applied, as rodents need to continuously feed upon them over several days for effective control. Due to continued and intensive use of FGARs over many years, some rodent populations of some species developed genetic resistance to them (Buckle 1994; Witmer 2019). The need for alternatives to manage FGAR-resistant populations led to the development of the more toxic SGARs.

Second generation anticoagulants (SGARs)

SGARs include bromadiolone, difenacoum, difethialone, flocoumafen and brodifacoum. These compounds are highly toxic by ingestion, presumed reproductive toxins and have long biological half-lives (CRRU 2021); thus, they are more persistent and bioaccumulative than FGARs (Eason et al. 2002; Vandenbroucke et al. 2008). Usually a single dose kills the target rodent, except against some species and anticoagulant resistant individuals (Buckle 1994). Of the SGARs, brodifacoum has the highest mammalian toxicity (lowest LD_{50} value), and difenacoum the lowest (Table 1). As with FGARs, SGARs are not only highly toxic to rodents but also for other warm-blooded animals, including humans, and are moderately toxic to invertebrates. The presence of SGAR residues in invertebrates (Shore and Coeurdassier 2018), songbirds (Walther et al. 2021) and non-target rodents (Brakes and Smith 2005; Geduhn et al. 2014), along with reported poisonings of domestic pets (Soleng et al. 2022) highlights the risk of primary exposure to non-target organisms.

SGARs have a long soil and water half-life and compounds accumulate in target and non-target organisms, as indicated by a high bio-concentration factor (Table 1). Due to the delayed action of FGARs and SGARs, there is no bait shyness, but poisoned rodents can live and be active for several days after bait uptake, as well as continue to feed on bait if available. This is especially of concern where genetic resistance to the SGAR has occurred. Secondary exposure to non-target animals that consume dead or dying rodents is common and almost impossible to prevent. Furthermore, another secondary exposure route includes the consumption of non-target invertebrates that feed on SGAR baits, such as slugs and snails (Alomar et al. 2018). There are thus numerous reports of AR residues in terrestrial predators/scavengers and avian predators/scavengers (Hindmarch et al. 2019; López-Perea and Mateo 2018), with multiple AR exposure potentially causing synergistic effects as well as cumulative effects (Lettoof et al. 2020). Also, because anticoagulant rodenticides take several days to kill the rodent, indoor use could potentially result in rodents dying under the house, in the roof or in a wall cavity where it is difficult to remove the carcass.

Aside from SGAR exposure to terrestrial non-target organisms, SGAR exposure and fate in aquatic environments also need attention, especially due to their acute toxicity to fish (Lewis et al. 2016). A recent review by Regenry et al. (2019a) highlighted that very little is known on this topic, but a number of studies have detected the presence of AR residues in fish, as well as other aquatic organisms, raw and treated wastewater, sewage sludge, and estuarine sediments. The authors concluded that the aquatic environment experiences a greater risk of anticoagulant exposure than previously thought, requiring more comprehensive monitoring data. Sewer baiting in particular has been identified as a significant emission source of SGARs in the aquatic environment (Gómez-Canela et al. 2014; Kotthoff et al. 2019; Regnery et al. 2020).

Due to the variability in rodenticide toxicity between different rodent species, the development of rodenticide resistance, including against some of the SGARs, or variability in neophobia between animals, chemical rodenticide treatment alone is unlikely to achieve sustained control in the long term (CRRU 2021). This becomes especially apparent when attempting large-scale municipal level control, where numerous unsuccessful examples exist (Easterbrook et al. 2005; Fernández et al. 2007; Lambropoulos et al. 1999; Lee et al. 2022). Thus, because of these issues, in addition to the environmental and human health risks and public opposition to chemical rodenticide use, more emphasis is needed on applying non-chemical methods of rodent management as described in the next section. Table 2 summarises advantages, disadvantages and effectiveness of the main groups of chemical and non-chemical methods.

Non-chemical rodent pest management methods

Cultural control

Preventative measures should be taken whenever possible to prevent rodent infestation. For household dwellings, food stores and indoor livestock holdings, this can be done to a certain degree by rodent-proofing buildings and blocking holes greater than 6 mm in diameter (UFAW 2021; WHO 1972). Close-fitting doors can be highly successful at keeping rodents out, but may not always be feasible. Other rodent exclusion methods include draft-sealing door strips, using galvanised wire mesh or a mix of small stones with mud or clay in openings, and repairing broken window and door

Table 2 Advantages and disadvantages of different rodent management methods for domestic rodent pest management

Method	Disadvantages	Advantages	Efficacy for short-term rodent control at a local scale (e.g. individual households/ buildings)
Acute rodenticides	High primary non-target exposure risk	Low secondary exposure risks, except bromethalin	Variable, as behavioural resistance can significantly reduce efficacy.
	Sub-lethal doses can lead to conditioned aversion (behavioural resistance)	Fast acting	(integrated approach with sanitation and proofing also needed to prevent re-invasion)
	No antidote available	A single dose is sufficient	
	Animal welfare concerns		
First generation anticoagulants	High primary non-target exposure risk	Low secondary exposure risk (except for coumatetralyl)	Can be effective if measures are taken to reduce genetic resistance development, e.g. limited use in an integrated approach with other methods such as trapping.
	Multiple doses required	Antidote available	(sanitation and proofing also needed to prevent re-invasion)
	Slow acting, can lead to bodies dying in wall/roof cavities	Bait aversion unlikely to develop (due to delayed effect)	
	High risk of genetic resistance developing among Norway rats and house mice		
	Animal welfare concerns		
Second generation anticoagulants	High primary non-target exposure risk	Antidote available A single dose is sufficient Bait aversion unlikely to develop (due to delayed effect)	Can be effective if measures are taken to reduce genetic resistance development, e.g. limited use in an integrated approach with other methods such as trapping.
	High secondary exposure risk		(sanitation and proofing also needed to prevent re-invasion)
	Slow acting, can lead to bodies dying in wall/roof cavities		
	High risk of genetic resistance developing among Norway rats and house mice (except for brodifacoum, difethialone, flocoumafen)		
	Animal welfare concerns		
Cultural control (e.g. rodent proofing and sanitation)		No animal welfare concerns	Can be effective if conducted properly as part of an integrated approach. Sanitation is especially effective when conducted at community/municipal scale
		No toxic hazards	
Physical control (e.g. trapping)	Animal welfare concerns	No toxic hazards	Can be effective if used as part of an integrated approach and if materials are of sufficient quality, e.g. traps with spring mechanisms of sufficient strength.
	Material quality may be poor, e.g. traps that are made with weak spring mechanisms		
	Single capture traps require regular checking/re-setting		
Biological control (e.g. fertility control, predators, biorodenticides)	Lack of evidence on efficacy	Fertility control/ predators have no known toxic hazards	Available evidence is limited.
	Lack of availability or under development		
	Potential hazards/animal welfare concerns		
	Predators may kill/injure non-target animals		

frames (Mari Saez et al. 2018; Mdangi et al. 2013). In situations, where it is not possible to rodent proof a food or grain store, stored food can be protected by keeping it inside closed containers, e.g. tins or claypots, with sealed lids or placing something heavy on top of a metal sheet lids, installing rat guards one metre above ground on the supporting legs of crib platforms, or surrounding grain sacks with wire mesh or fishnetting (Brown et al. 2020; Htwe et al. 2021, 2017; Mdangi et al. 2013).

Rodent-proofing should be also accompanied by sanitation, such as removing potential food, water and harbourage (FWAH), to make the habitat less attractive to rodents and reduce the availability of resources that support rodent population growth. A systematic review of the literature on municipal-scale urban rodent control by Lee et al. (2022) reported that removing FWAH is widely considered to be the most effective method of reducing rats. Within and around buildings, the availability of a wide range of materials will provide habitat for rodents. Rodents often find harbourage within rubbish, debris or other materials lying around buildings, overgrown vegetation or ditches and drainage systems. These areas should be kept as clean and tidy as possible to make them less attractive to rodents as places to live and breed (WHO 1972). Within households, it is important to clean up spills and crumbs, store food in closed containers and cover rubbish bins with tight-fitting lids (UCT 2019). Furthermore, closing sewers, improving drainage, and maintaining sanitation around water bodies are important to reduce available water supply in urban environments (Zeppelini et al. 2021).

There are devices available to detect rodent infestation early on (Fuelling et al. 2011). For field rodents, forecast models are available to indicate the risk of rodent outbreaks (Esther et al. 2014; Krebs et al. 2004; Leirs et al. 1996) and associated risk of human infection with rodent-borne pathogens (Kazasidis and Jacob 2023). However, such predictive models are still lacking in urban settings. Forecasting gives the opportunity for timely management action before a rodent problem gets out of hand. In areas where rodents pose a significant problem, factors that contribute to the presence of rats extend beyond individual properties (Lee et al. 2022), thus coordinated community wide campaigns are recommended to remove FWAH and conduct trapping and/or rat hunting. For example, studies in Asia demonstrated significant reductions in rodent numbers and losses to stored grain following intensive daily trapping at the community level together with improved hygiene practices (Belmain et al. 2015). Permanent working groups for rodent management in agriculture (Brown et al. 2024) ensure the involvement of stakeholders and similar structures may serve this purpose in domestic rodent control. In towns and cities, large- or municipal-scale strategies are needed to comprehensively address infestations and their causes (Lee et al. 2022).

Physical control

If rodent infestation occurs in an urban or domestic setting, there are a number of alternatives to rodenticides available. Trapping using live or kill (snap or break-back) traps is often recommended for rodent control in and around buildings and small farms. For example, in household grain stores in Bangladesh, daily trapping was found to be as effective as the use of rodenticides, with the added benefit that the traps could be re-used for many years (Belmain et al. 2015; Krijger et al. 2020). In Uganda, trapping in individual households was highly effective at removing all rodent pests within a 16-day period (Eisen et al. 2018). Following a study in which high quality rat traps were provided to 200 households in poor urban communities in South Africa where poor sanitation, infrequent refuse removal and overcrowded living conditions led to high rodent infestations, over half of study participants that previously used pesticides for rodent control voluntarily stopped using pesticides (Roomaney et al. 2012). Another study across three African countries showed that community household trapping effectively reduced rodent pest populations and damage to stored grains (Taylor et al. 2012). The results of these studies thus indicate that trapping is effective, feasible and acceptable.

Of the many types of rodent traps, good quality snap traps are considered to be the most effective and humane (UFAW 2021). Newer types of kill traps have also been developed such as battery-powered traps that deliver an electric shock or a captive bolt that kill rodents quickly. However, it is essential before setting kill traps, especially those used outdoors for rats, to consider both the target animals and any other animals that may be present and may enter traps accidentally as they can also injure or kill non-target animals (Witmer 2019). To minimise the risk to children, non-target animals, livestock and pets, traps should not be set where they may come into contact with them or tamper-resistant boxes should be used (UFAW 2021).

Using the appropriate trap and bait for the situation and target species is important for achieving high efficacy (Burke et al. 2021; Witmer 2019). Trapping can be cumbersome and difficult to conduct when rodents are trap shy or present in structures that are hard to access for trap placement. Behavioural studies highlight that rodents are creatures of habit and prefer to follow the same runways, thus identifying these runways, such as by sprinkling a fine layer of flour or baby powder, and placing traps along these will improve their success (WHO 1972). Devices have also been developed to assess the technical properties of traps (Baker et al. 2012; Walther et al. 2024). Snap traps that have a double-peg type spring and a wide opening angle are likely to produce a more powerful trap, which is more likely to kill rodents quickly and humanely (Baker et al. 2012; UFAW 2021). Further guidance on how to evaluate the animal welfare impact and efficacy of snap traps was recently produced by an expert working group in EU, with the goal of establishing a voluntary certification scheme (Schlötelburg et al. 2021). This has subsequently been used by the German Environment Agency to test several types of traps and identify those that meet minimum welfare standards (UFAW 2021).

Another type of trap includes glue (or sticky) boards that captures rodents using a non-toxic sticky substance and holds it until it is either removed or until it dies. However, they are indiscriminate and present serious animal welfare concerns and are hence banned in several countries (CRRU 2021; UFAW 2021). Numerous studies have aimed to identify compounds that repel rodents or to drive them away using (ultra)sound or vibration. This may help to mitigate the problem at the place where repellents are used but simply relocates the problem. However, habituation usually sets in sooner or later, especially if there is an attractive food source for them (Meehan 1984), and the efficacy of repellents and repellent devices is often poor (Hansen et al. 2016; Lund 1988).

Biological control

Biological control is often advocated as an appropriate technique to manage pest rodents. In urban/domestic settings, predators, such as cats, are frequently suggested to reduce the impact of rodents, yet there are very few studies evaluating their impact. One study in Eswatini found that the combined presence of cats and dogs at homesteads can reduce rodent foraging activity at experimental seed trays and movements of rodents (Mahlaba et al. 2017), but it is unclear how rodent abundance, damage and disease risk are affected by biocontrol with predators (Labuschagne et al. 2016; Ostfeld and Holt 2004). A number of parasites and diseases have been trialled against rodents in agricultural settings. However, few are commercially available. A rodent-specific parasite, *Sarcocystis singaporensis*, does not affect humans and has been trialled effectively in towns in Laos and in rice fields in Thailand (Jäkel et al. 2006, 2019). ‘BIORAT’, produced in Cuba, is a combination of warfarin sodium 0.02% + *Salmonella enteritidis* var. Danysz Lysine. However, there are no published data in mainstream literature to support or refute the use of BIORAT. In addition, both warfarin (a FGAR) and *S. enteritidis* are of human health concern (Brown et al. 2017).

Other biological control methods that are being investigated include fertility control to minimise proliferation of rodents by restricting reproduction instead of culling them (Jacoblinnert et al. 2021). This method is favoured by the public over using rodenticides to manage red squirrels (Dunn et al. 2018). Fertility control could minimise recolonisation by infertile residents that defend their territories against (fertile) immigrants. Only few fertility control products are registered for use against rodents. They include ContraPest® (a combination of 4-vinylcyclohexene diepoxide and triptolide for black rat (*Rattus rattus*) and Norway rat (*R. norvegicus*) in the USA) (Pyzyna et al. 2016; Siers et al. 2017), EP-1 (a combination of levonorgestrel and quinestrol for multimammate mice (*Mastomys natalensis*) in Tanzania) (Massawe et al. 2018; Selemani et al. 2021), and GonaCon™ (injectable product for black-tailed prairie dogs (*Cynomys ludovicianus*) in the USA) (Shiels et al. 2023). It is important that anti-fertility compounds are effective and safe for non-target species, present no risk to humans and the environment and are economically feasible. Assessments of the environmental fate of quinestrol and levonorgestrel indicate a short half-life in soil (1–2 weeks) and water (a few hours) (Tang et al. 2012a, b). However, a recent review of rodent fertility control by Massei et al. (2023) concluded that studies on the persistence of oral contraceptives in the environment and in the food chain were generally under-reported. For domestic rodent management in sensitive areas where tolerance for rodent infestation is low, fertility control may take too long to achieve the desired management aims. However, recent simulations show that fertility control using contraceptive bait may substantially reduce rodent populations when sustained over multiple rodent generations (Shuster et al. 2023).

Integrated pest management

There is a general dilemma in rodent control. The aim is to reduce the population of a mammalian species considered as pests that has many similarities in morphology and physiology to “wanted” mammalian species including humans. Whatever is bad for the rodent, often is also bad for non-target species. Welfare concerns regarding the use of acute rodenticides are also valid for FGARs and SGARs (Table 2). Welfare concerns may also relate to trapping and biocontrol because traps and predators alike can injure or kill rodents or non-target organisms (Parsons et al. 2018). Some studies have also revealed increased pathogen prevalence/transmission in surviving animals following efforts that focused on lethal control, such as with leptospirosis in rats (Lee et al. 2018), and killing rats in endemic plague foci could lead to the dispersal of rat flea vectors (Belmain 2018; Rahelinirina et al. 2023). Furthermore, reliance on a single method tends to lead to declining effectiveness over time, such as from genetic rodenticide resistance that is a common problem in some urban rodent populations (Witmer 2019). Municipal-scale approaches that focus on lethal control measures rather than addressing causative FWAH factors often fall short of methodological expectations (Lee et al. 2022). This highlights the importance of emphasising preventative action rather than only relying on reactive approaches, such as rodenticide use (Byers et al. 2019; Colvin and Jackson 1999).

To have the greatest success in the long-term, an integrated approach (i.e. integrated pest management, integrated rodent management or ecologically based rodent management) is needed that considers environmental, ecological and socio-economic factors, with chemical pesticide use as a last resort (Brown et al. 2020; Lambropoulos et al. 1999; Rahelinirina et al. 2023; Witmer 2019). In urban environments, this requires careful planning, cooperation and coordination between local authorities, communities, and pest control operators to take into account the complexity of rat management (Awoniyi et al. 2024; Dalecky et al. 2024; Lambropoulos et al. 1999; Lee et al. 2022). Ongoing resourcing and funding to eliminate factors contributing to FWAH is essential to prevent rodent populations returning to pre-infestation levels (Lee et al. 2022). Community cooperation and awareness raising are also vital in rural communities where rodents have the opportunity to move from house to house. In addition, more attention and research are needed for non-lethal methods, early detection and prediction of rodent problems. Periodic monitoring of rodent populations is an often-overlooked component of rodent management that can instruct appropriate action(s) to be taken before a rodent population builds up (Witmer 2005). The next section provides examples of integrated approaches implemented in LMICs.

Case studies of effective alternatives for domestic rodent pest management

Urban rodent control in Brazil

Household rodent infestation is a major concern in most disadvantaged urban communities often called "favelas" of Brazil (Costa et al. 2014; Masi et al. 2010). Poor sanitation facilities and waste management in addition to dilapidated structures and the continued increase in the numbers of disadvantaged urban dwellers foster the proliferation of rodent populations in these communities. Rodents are reservoirs of important zoonotic pathogens (Costa et al. 2014) and are capable of destroying agricultural products and household properties worth billions of dollars per year (Childs et al. 1991) therefore necessitating regular control efforts.

A number of methods have been used for controlling rodent proliferation in Brazil, e.g. rodent trapping, application of rodenticides, habitat modification, sanitation interventions, education interventions (e.g. "rato fora" or "rats out") and lately the combination of two or more of these methods, i.e. integrated rodent management—"IRM" (de Masi et al. 2009). Until recently, the application of rodenticides/pesticides was the principal control method (de Masi et al. 2009; Papini et al. 2019; Pertile et al. 2022). Possibly because it is cheap, readily available and easy to apply. While rodenticides of coumarin derivatives such brodifacoum and coumatetralyl are legally authorised in Brazil (FUNASA 2002), the application of other illegal rodenticides/pesticides, such as aldicarb (locally known as "chumbinho"), have been well documented in the country (Panis et al. 2021; Papini and Nakagawa 2014).

Reports of bait shyness, rodenticide resistance and the negative results from the sole application of rodenticides in Brazil (with rodent populations quickly returning to the pre-intervention state in 3 months after the chemical application) (Babolin et al. 2016; Pertile et al. 2022), together with the killing of non-targeted species and death of residents (Panis et al. 2021; Papini and Nakagawa 2014) have necessitated a paradigm shift from the sole application of chemical application during rodent control campaigns. For example, the number of poisonings and suicides among the Brazilian population resulting from rodenticides application totalled 26,651 and 16,867 between 2005 and 2011 (Papini and Nakagawa 2014). Additionally, the reporting rate of accidental and intentional human poisonings arising from rodenticides was 64.5 per 100,000 population, and 58.7 per 100,000, respectively, within the same period (Panis et al. 2021).

Therefore, researchers and other stakeholders in Brazil have continued to advocate in favour of IRM techniques during rodent control programmes (Awoniyi et al. 2022; de Masi et al. 2009). One example of an effective IRM programme in Brazil includes a study conducted in Sao Paulo (de Masi et al. 2009). The authors of this study reported that the rodent infestation rate reduced from 40% pre-intervention to 14.4% (64% percentage reduction) post-intervention following a combination of (i) chemical application (coumarin-based rodenticides), (ii) a waste management campaign (improvement of the surrounding environment to limit rodents' access to food, water and harbourage), and (iii) an education intervention (community awareness programmes on TV, radio, and five local schools about the importance of preventing household rodent infestation and the procedures to achieve this).

Another example in Brazil, conducted by a group from Salvador combined (i) a chemical-based intervention (coumarin-based rodenticides application) that lasted one week, (ii) an education intervention that lasted throughout the study period (involving regular information campaigns to remind residents about the need to practise proper waste disposal and to keep pets' food/water away from the reach of rodents), and (iii) a local government led infrastructural/environmental intervention that was conducted during the first year of the study and involved the modification of open sewers and pavements in common spaces and sidewalks to reduce rodents' sources of food, water and harbourage

(Fig. 1) (Awoniyi et al. 2022). As a result of these interventions, there was a significant sustained reduction in the rodent infestation rate from 70% before, to about 20% after the interventions, offering a 71% reduction over approximately 12 months (T3–T5 of Fig. 2). The percentage reduction here is similar, but the effect lasts longer than most metal phosphides applications (Eisemann et al. 2003). To ensure the effectiveness of the intervention, three valleys (1, 2 & 3) with similar socio-environmental features were used for the study. Valleys 1 and 3 served as the chemical-treatment valleys and received all three categories of the interventions, while valley 2 received no chemical intervention. The long-term reduction in rodent infestations observed in all 3 valleys indicates that IRM technique is more effective in controlling the long-term population of rodents than the sole application of a control method (i.e. as practised prior to the intervention), particularly in disadvantaged urban communities. However, supplementing educational and infrastructural interventions with a chemical approach did not provide any noticeably greater benefit.

The two case studies from Sao Paulo and Salvador suggest there are alternative practicable ways of controlling the urban proliferation of rodents without predisposing residents and other non-target species to probable poisonings arising from the exclusive application of hazardous rodenticides/pesticides (Papini and Nakagawa 2014). Brazilian favelas are unplanned, characterised by inadequate sanitation facilities with most residents either unemployed or low-income earners, with most residents unable to afford sustainable IRM techniques, such as rodent-proofing buildings. Given the socio-economic situation of these communities, it is thus important for local governments to drive major rodent control programmes and to continue to support interventions (including infrastructural maintenance) to prevent rodent populations from reverting to pre-intervention levels (Awoniyi et al. 2021; Richardson et al. 2017).

Community ecologically based rodent management (EBRM) in rural households in Ethiopia

In Ethiopia, over 100 species of rodents have been recorded, with only 10 species considered to be significant pests. The main pest species (both field and storage) belong to the following six genera: *Arvicanthis*, *Gerbilliscus*, *Mastomys*, *Stenocephalemys*, *Tachyoryctes*, and *Rattus*. Rodenticide (mainly ZnP) application and trapping are two of the most practised rodent management methods in crop fields and storage areas in northern Ethiopia (Meheretu et al. 2022, 2010). However, the use of rodenticides in storage areas and houses presents a significant health risk to humans and domestic animals (Dalecky et al. 2023; Meheretu et al. 2022). For instance, a retrospective cross-sectional study from Debre Tabor general hospital, a district hospital in northern Ethiopia, revealed that out of the 102 patients admitted to the hospital presenting acute poisoning between September 2013 and August 2016, rodenticide poisoning accounted for 56.9% of the cases, with a mortality of 18.6% (Endayehu and Shenkutie 2019). In a study in northern Ethiopia, 93% of surveyed cereal farmers reported the use of zinc phosphide rodenticide in rainfed crop fields to manage rodent pests (Meheretu et al. 2010). About 87% of these farmers decided to buy (apply) the rodenticide after noticing intense rodent activities in the fields, suggesting that rodent management is conducted in response to rodent damage, rather than integrated into routine pest management activities.

Traditional storage is often rudimentary and may, for instance, consist of bamboo mats held loosely together. These open storages attract vermin and rodents close to where people live, increasing the risk of zoonotic transmission, as well as causing food losses and contamination. Furthermore, inadequate waste disposal, grain and cattle feed storage methods aid the proliferation of rodent populations in villages thereby heightening public health concerns.

Poor knowledge of rodent management methods, including rodenticides, likely results in weak efficacy of action and treatment failure, as well as a public safety concern, leading to apathy and widespread acceptance of rodent pests in fields and storage areas (Meheretu et al. 2022). However, for the farmers in the highlands of Amhara, the problem became so severe, they reached out to the extension workers for help. This led to the development of a successful community-level EBRM programme that involved extension workers, Meta-Meta, a Dutch social enterprise, and the Amhara Bureau of Agriculture (Dalecky et al. 2024).

Due to a huge knowledge gap on alternative biological and ecological rodent management methods for small-holder farmers in Ethiopia, the programme began by developing a systematic, communal, and ecologically based approach from the ground up. This entailed engaging with farmers and communities to understand the extent of the problem followed by combining their indigenous knowledge with scientific research to work towards a sustainable solution. The steps for the development of community-level EBRM were as follows:

1. Focus group discussions and surveys on the knowledge, attitudes and perceptions were conducted with farmers in the highlands of Amhara.
2. Local knowledge was combined with academic research to develop alternative methods, i.e. a biological rodenticide using locally available botanicals and an EBRM package (Dalecky et al. 2024).
3. Trainings were held twice a year for agricultural experts, community leaders and watershed user associations (WUA) committees. Farmers in the highlands

of Amhara are organised in WUAs, which are registered under the regional government and responsible for watershed management (mainly soil and water conservation practices) as a community. Each WUA has an average area of 500 hectares and 150–200 households. The fact that the watershed community made the EBRM activities part of their collective work was critical to the success of EBRM in the area.

4. The WUA committees thereafter continued action planning with all WUA members. In action planning, they incorporated the timing of the EBRM actions in the lean season (i.e. when rodent populations are still at lower density) and factored in the importance of collective action (e.g. a by-law was created specifying that any household who did not join in a collective activity such as flooding rodent burrows, would pay a penalty fee).
5. Activities implemented as part of the EBRM package included: measures to expose rodents to predators, removing harbourage, deep ploughing, flooding and plugging rodent burrows, setting up stone traps, using domestic cats (mainly in homesteads), and storing grains

Fig. 1 Infrastructural intervention in Pau da Lima, Salvador-BA, Brazil; **a** typical open sewer in Pau da Lima, **b** cross-sectional area of an aspect of the community during the intervention, and **c** modification of sidewalks to reduce sewer water accumulation

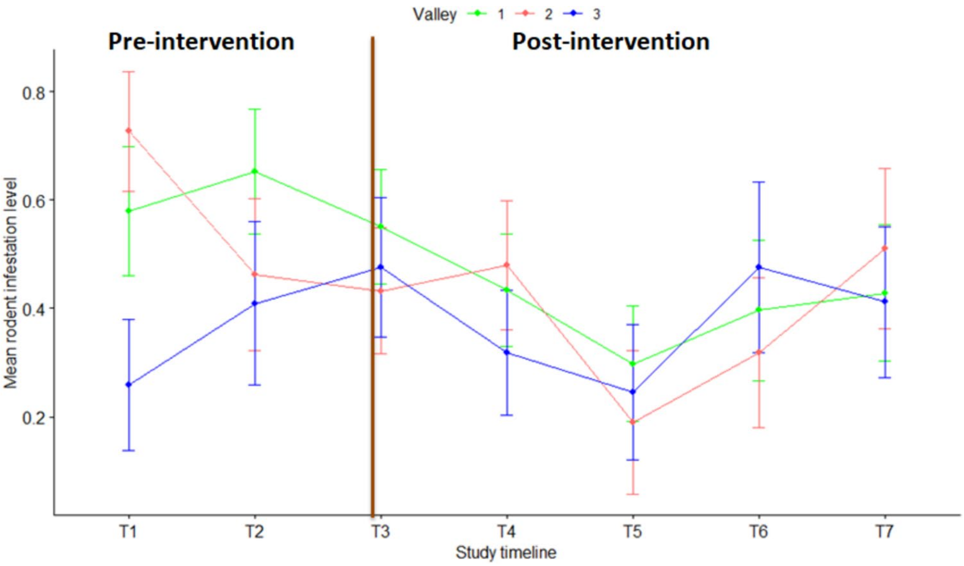

Fig. 2 Mean (±95% confidence interval) rodent infestation levels in three valleys (valley 1 & 3 = chemical-treatment; valley 2 = non-chemical treatment) from 2014 to 2017. Each survey period, i.e. T1–T7, lasted 3–4 months (adapted from Awoniyi et al. 2022)

in locally made rodent-proof storage structures (e.g. see Fig. 3).

6. These EBRM activities were organised through campaigns, ensuring regular interventions with all households involved.

As well as reducing the pesticide poisoning risk, the EBRM campaign led to a substantial improvement in rodent control in comparison with prior efforts that relied principally on rodenticide use. A post-implementation survey with the WUA committee members from all of the watersheds that were included in the EBRM campaigns indicated that farmers perceived that rodent damages had been cut by a magnitude of up to 50% after two years of implementing EBRM. The survey also indicated that through horizontal learning, the uptake of the EBRM activities increased by up to threefold in the neighbouring watersheds that were not included in the EBRM campaigns. Currently, in 2023, there are at least 65 watersheds implementing EBRM, benefiting up to 13,000 households and covering about 33,000 hectares of land.

This case study focused on rural communities, including their homesteads, in an agricultural landscape. However, the lessons learned from EBRM within and around homesteads also provide useful guidance for rodent management in urban and peri-urban areas. Most notably, the case study highlights the need for community action with a focus on reducing the availability of food and shelter for rodents, for example, via proper garbage disposal, rodent-proofed storage and regular sanitation of houses, storage areas and gardens.

Policy recommendations

Following the literature review, we identify the following policy recommendations (summarised in Table 3).

Recommendation #1: restrict availability

Given the high proportion of poisoning cases associated with metal phosphides in LMICs, and the lack of an effective antidote, we recommend limiting access to this group of rodenticides. Restricting access to the means of suicide is also a globally accepted evidence-based intervention for suicide prevention, by giving persons in distress time for acute crises to pass (Utyasheva and Eddleston 2021; WHO 2021). In descending order of effectiveness, restricting pesticide access can include either 1) an outright ban of the chemical (the most effective and highest level of the industrial Hierarchy of Control, a well-established method of ranking risk reduction measures (UNEP et al. 2022); 2) a ban of a certain formulation type; 3) limiting access by type of end-user, e.g. via professional certification; 4) limiting access by type of supplier; and/or 5) enforcing restrictions on how/where pesticides are stored (Eddleston and Gunnell 2020; UNEP et al. 2022; Varghese and Erickson 2022).

There are several studies that show that overall suicides have decreased following outright bans of acutely toxic HHPs (Knipe et al. 2017; Yan et al. 2023). With regard to metal phosphides, the results of bans have been mixed. In north India, AlP poisoning was the primary cause of poisoning-related deaths until 3 g 56% AlP tablets were banned from open sale in 2001. After which, AlP-related deaths fell dramatically, indicating a significant public health and pesticide regulatory success (Karunarathne et al. 2021). Preliminary results from Nepal (Ghimire, R. unpublished) also indicate that a switch from 3 to 12 g AlP tablets, which are less easily ingested, has resulted in a reduction in all poisoning deaths. However, in Iran, the ban of 3 g tablet formulations in 2007 did not achieve such success due to the continued availability of 3 g tablets via illegal imports (Etemadi-Aleagha et al. 2015; Hashemi-Domeneh et al. 2016). This highlights that when implementing bans in countries that have porous borders, there is the added need for strengthening border controls and/ or a regional approach between neighbouring countries (OECD 2014; Stuart et al. 2023; UNEP et al. 2022).

The availability of ZnP formulations at concentrations as high as 80% also poses an unnecessary and added risk to human health. For example, in the US, most occupational exposure incidents to ZnP between 2012 and 2019 involved exposures to products containing either 62% or 67% ZnP (EPA 2022). In many LMICs, ZnP is commonly available as an 80% wettable powder formulation as a low-cost premix for bait (Bhandari and Basnet 2022). However, 1 grain of 2.5–5% pre-mixed wheat bait is sufficient to kill a 15 g mouse and 3–5 grains of 2.5% bait is sufficient to kill a 150 g rat, demonstrating the effectiveness of much lower dose formulations which pose a reduced human health risk (Staples et al. 2003). In the US, 80% ZnP wettable powder formulations are no longer permitted. In EU countries, the highest concentration of ZnP in registered products is 3% (EPPO 2023), with similar restrictions in place in other countries, such as Australia and New Zealand (Eason et al. 2013; Hinds et al. 2023). Thus, it seems clear that, as a minimum, countries should ban the sale and production of the most hazardous metal phosphide formulations, such as small AlP tablet formulations and high concentration ZnP formulations, as well as prohibit the sale and use of other metal phosphide formulations for household use and for unlicensed users.

Recommendation #2: implement enforcement of restrictions

Unfortunately, introducing bans and restrictions in use is not sufficient if there is no action to enforce such policies. In many LMICs, the illegal street trade in unregistered or restricted-use rodenticides and other pesticides for rodent control is common and some of these pesticides may be just as hazardous as metal phosphides (Dalecky et al. 2023; Rother 2016). For example, in Brazil and South Africa, aldicarb and terbufos, both highly hazardous insecticides, are illegally sold by street vendors and used for rodent control, contributing to frequent fatal human poisoning cases (Davies et al. 2023; Panis et al. 2021; Papini and Nakagawa 2014; Rother 2016). Indomethacin, an anti-inflammatory drug for pain-relief in humans, is also illegally used as a rat poison in several African countries (Dalecky et al. 2023; Donga et al. 2022). It is thus important to follow up bans and restrictions with regular inspections and enforcement, along with public education regarding the dangers of such pesticides (Papini and Nakagawa 2014).

Recommendation #3: improve the availability of less hazardous alternatives

This review identifies effective alternative options for rodent pest management in urban and domestic environments, especially when conducted in an integrated approach. We recognise, however, that these may not always be available or affordable, or the end-user knowledge about such alternatives and integrated approaches may be lacking (Rother 2016). To address this, government investment is needed in public information/awareness campaigns on alternative approaches to rodent pest management and the hazards of various chemical pesticides that are locally available (including illegal pesticides as indicated above). Due to the hidden costs from human pesticide poisoning, such as medical costs and related burdens on health services and society, there is also an economic argument for government subsidies to help make effective low-risk methods, such as traps, more affordable and available (UNEP et al. 2022). As identified in this review, providing rodent traps to poor urban communities, along with guidance on how to use them, has been proven to reduce demand for illegal as well as legal pesticides for rodent control (Roomaney et al. 2012).

Fig. 3 A rat-proof storage system developed by Mr Sisay Mengistie, a farmer from Ata Meher watershed. It is a square two-metre high container made of wood and corrugated iron that is sealed with a door and used to store wheat and barley. It is well suited for local adoption: the materials are available locally at a reasonable price, it is easy to build and adaptable, it can store large quantities of grain: up to 1500 kg per storage structure

Other important points to consider when promoting less hazardous alternatives include social barriers to adoption and the quality of the alternative options available—such as the strength of trap spring mechanisms, which can affect their efficacy and humaneness (Baker et al. 2012). By understanding such issues, interventions can be better targeted to address them. For example, during a recent household survey in New Zealand, one of the main concerns for household rat trapping for conservation aims was the perception that traps are a cruel and inhumane way to kill animals (Kaine et al. 2023). In response, the authors of the study recommend that promotional campaigns seeking to promote trapping should emphasise on the safety of traps, and the speed and efficacy with which they function. Public and private investment should also prioritise the development of low-risk methods (UNEP et al. 2022), such as supporting local trap producers to produce high quality traps at low cost and implement measures to minimise non-target risk.

If selecting substitute chemical rodenticides to replace metal phosphides, the least toxic rodenticides (including their formulations) should be prioritised over more toxic rodenticides following a careful risk and hazard assessment. The FAO/WHO International Code of Conduct on Pesticide Management recommends that governments should “make every reasonable effort to reduce risks posed by pesticides by making less toxic formulations available” (FAO and WHO 2014). Particular attention to this matter will be necessary in countries where the only alternative rodenticides available are those that also pose high levels of risk to humans and the environment. For example, for West African countries that implement the common regulations set by Sahelian Committee for Pesticides (CSP), the only rodenticides registered are brodifacoum and ZnP (CILSS 2022). When comparing anticoagulant rodenticides, Berny et al. (2014) identify that for rat control, FGARs and less potent SGARs should always be considered as the first choice. SGARS should only be used against rats, where there is evidence that infestations are resistant. However, because FGARs have low efficacy

Table 3 Key recommendations from this literature review

Recommendations	
1 Restrict availability	· Ban the sale and production of the most hazardous metal phosphide formulations, such as small AlP tablet formulations and high concentration ZnP formulations, as well as prohibit the sale and use of other metal phosphide formulations for household use and for unlicensed users. · In countries that have porous borders, strengthen border controls and/ or a regional approach between neighbouring countries.
2 Implement enforcement of restrictions	· Follow up bans and restrictions with regular inspections and enforcement, along with public education regarding the dangers of such pesticides
3 Improve the availability of less hazardous alternatives	· Invest in public information/awareness campaigns on alternative approaches to rodent pest management and the hazards of various chemical pesticides that are locally available. · Public and private investment should also prioritise the development of low-risk methods. · Conduct careful risk and hazard assessments if selecting substitute chemical rodenticides to replace metal phosphides so that the least toxic rodenticides (including their formulations) are prioritised over more toxic rodenticides.
4 Promote and invest in preventative measures, including community action	· Invest in sanitation and infrastructure to mitigate rodent infestations in urban and domestic environments, especially in lower-income areas. · Conduct government-led rodent management interventions and education/awareness campaigns at a community-level.
5 Strengthen research on less hazardous alternatives	· Fund further research to develop less hazardous alternatives that are economically viable and socially acceptable. · Conduct studies for different contexts and social-economic conditions to develop locally adapted approaches that balance risk, cost and efficacy.

against house mice, FGARs should only be used against mice where there is evidence that the local strain is susceptible, otherwise SGARs should be considered as the first choice. With regard to non-target risk, brodifacoum was ranked as posing the greatest overall potential risk to birds and mammals out of 9 rodenticides analysed (Erickson and Urban 2004). With regard to primary non-target risk, ZnP ranked the highest, with brodifacoum second. With regard to secondary non-target risk, brodifacoum ranked the highest, while ZnP ranked the lowest.

Recommendation #4: promote and invest in preventative measures, including community action

Both the case studies presented in this review highlight that investments in sanitation and infrastructure are essential to mitigate rodent infestations in urban and domestic environments. Reactive approaches to urban/domestic rodent management that do not address the underlying features that promote rat abundance are unlikely to be effective in the long term (Byers et al. 2019). Removing sources of food, shelter and water can prevent rodent population build up and thus negate the need for metal phosphides and other forms of lethal rodent pest control. However, this important first step towards sustainable rodent pest management is often neglected and so government investments in such measures are essential, especially in lower-income areas due to infrastructure disinvestment and lower coping capacity of residents (Awoniyi et al. 2024; Jassat et al. 2013; Peterson et al. 2020). Long-term investments in such measures are also needed so as to prevent rodent populations from reverting to pre-intervention levels.

It should also be highlighted that although the same principles of cultural control apply, the approach of such interventions should be tailored to the local context. For example, the approach needed for a rural community with grain stores and scrub vegetation will be quite different to that needed for an urban poor community with overcrowding and open sewers. Overall, community action and area-wide interventions that consider the ‘total environment’ for sources of FWAH are essential due to the ability of rodents to move between households (Byers et al. 2019; Lee et al. 2022). It is thus important to conduct rodent management interventions and education/awareness campaigns at a community-level and for governments to lead these.

Recommendation #5: strengthen research on less hazardous alternatives

Due to a variety of welfare, hazard and economic concerns from most of the existing rodent pest management methods available, there is clear need to fund further research to develop less hazardous alternatives that are economically viable and socially acceptable. Research to further develop and demonstrate the effectiveness of non-toxic alternatives such as biological control, fertility control, physical exclusion and trapping should be prioritised, as well as carefully assess and monitor any potential risks. Studies are also needed for different contexts and social-economic conditions to develop locally adapted approaches that balance risk, cost and efficacy (e.g. see Stuart et al. 2020). This requires optimising current methods, developing new methods and using a combination of several methods in an integrated approach.

Conclusions

Due to their high toxicity, rapid onset of systemic symptoms and lack of specific antidote, metal phosphides pose a high risk to human health, particularly if used inappropriately or for intentional poisoning. This is especially apparent for many LMICs where they are widely available to the public, perhaps due to lack of bans and restrictions or lack of enforcement. Our review of the literature, along with case studies, shows that there are numerous alternative methods for managing rodent pests in domestic/urban settings that can replace metal phosphides. These include chemical and non-chemical methods. However**,** because the majority of chemical rodenticides qualify as HHPs due to acute human health toxicity, environmental toxicity, and/or bioaccumulation, strategies that simply select substitute chemical rodenticides to replace metal phosphides should be approached with caution as these are likely to replace one set of hazards with others. Thus, these will need to be carefully assessed. In addition, there is the added risk of AR resistance development. It is evident that overall, we need to move away from current levels of rodenticide reliance and move towards more integrated and ecologically based approaches.

Author contribution

AMS, ME, SW, SW and JJ conceived the study. AMS and JJ conducted the literature search. YM, LB, AMA and FC provided the case studies. AMS, JJ, AMA, FC, LB and JM wrote the first draft. All authors critically revised the manuscript and approved the final version.

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Declarations

Conflict of interest The authors declare no conflict of interests.

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