Common insect pests in homes and cultural heritage sites

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ABSTRACT

Insect pests represent a threat to the integrity of historic buildings and homes, causing serious losses and irreversible damage. These pests can cause extensive damage to organic materials, including wood, textiles, and paper. Beetles, termites, booklice, moths, and cockroaches are just some of the main insect pests that are frequently found in historic buildings and homes. Beetle species such as the furniture beetle and the powderpost beetle are well recognised for their capacity to infest and feed on wood. Termite infestations can remain undetected and cause considerable damage that may even lead to the complete destruction of a building's structural integrity. Cloth moth larvae are known to damage textiles, including carpets, furniture, clothes, and tapestries. Some wood-destroying species of cockroaches have the potential to harm historic buildings. Booklice have the ability to eat cellulose fibres found in archived articles and artefacts stored in heritage buildings, causing deterioration and damage to documents over time. This article reviews the literature and presents an overview of the major insect pests belonging to five known orders Coleoptera, Blattodea, Lepidoptera, Zygentoma (long-tailed silverfish) and Psocoptera, which pose a threat to households, museums, depositories, libraries, and cultural heritage buildings. We also discuss their biology, their impact on human health, and the various potential approaches to identifying them.

Subjects Entomology

Keywords Psocoptera, Lepidoptera, Coleoptera, Building, Insect pests, Blattodea, Zygentoma (long-tailed silverfish), Human health, Cultural heritage, Museum

INTRODUCTION

A number of pests, including rodents, bats, and insects pose a risk to the structural integrity of collections and objects stored in homes and museums. These pests can invade organic artefacts, causing damage that is both visually striking and structurally devastating (*Strang & Kigawa, 2009*; *Brimblecombe, Jeannottat & Querner, 2023*). This destructive impact on cultural heritage reveals a troubling paradox: while insects and other pests play important roles in ecological processes such as decomposing organic matter, their impact on our irreplaceable historical and artistic legacies can be profoundly damaging (*Brimblecombe & Querner, 2024a*).

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An insect pest can be defined as any insect whose presence causes harm to human interests, particularly in homes and museums, where they pose a risk to valuable objects and collections. They often infiltrate homes and museums through infested objects, particularly those that are newly acquired or on loan. These pests are frequently transported unknowingly during trade or travel, making their way into collections (*Fenn-Moltu et al., 2023*). Once at their destination, the risk they pose depends not only on the object they infest but also on the specific material involved (*Williams, 1947*). The presence of these insects in homes and museums can lead to substantial economic losses, impacting both integrated pest management (IPM) efforts and the preservation of valuable objects (*Bradshaw et al., 2016*). Particular traits such as their size, mobility, reproductive capabilities, and developmental stages contribute to these issues (*Querner et al., 2013*; *Brimblecombe & Querner, 2024b*). For example, the larval stages of beetles (Coleoptera) and moths (Lepidoptera) can cause significant physical damage by chewing or tunnelling through materials, leaving behind holes, frass (insect excrement), and webbing (*Bradshaw et al., 2016*). Furthermore, insects have specific feeding preferences, which means that their impact varies according to the material, hence the need to assess the substance rather than the object itself (*Olaboro et al., 2024*). In particular, various species of silverfish (Zygentoma) are particularly problematic in museums, as they tend to damage cellulose-containing objects such as paper, books, and archive materials, as well as tissue paper, cardboard, wallpaper, textiles, and materials containing starch and sugars (*Brimblecombe & Querner, 2021*).

In dwellings, buildings, and museums, many insect species seek out food and shelter, becoming persistent pests. Termites and cockroaches (Blattodea) are particularly troublesome, causing structural damage to both modern and historic structures. In areas with high humidity, such as certain spaces in homes and museums, Psocoptera (commonly known as booklice) are often found. They feed on mould, fungi, and occasionally dead insects, making them a serious concern in museums, where they can damage organic materials including paper, books, and textiles (*Chin et al., 2010*).

In addition to these pests, beetles (Coleoptera), moths (Lepidoptera), and silverfish (Zygentoma), including the long-tailed silverfish, pose a significant threat to both historic and non-historic buildings (*Brimblecombe et al., 2023*). These insects are difficult to detect at an early stage, and often go unnoticed until an infestation is well established, making their control more challenging. Once established, they can cause extensive damage to materials such as wood, fabrics, and other organic matter, further complicating preservation efforts in homes, museums, and heritage sites (*Trematerra & Pinniger, 2018*).

Although numerous studies have addressed infestations of historic buildings, museum objects, books, and collections by household pests, and have explored various management approaches (*Querner, 2015*; *Querner et al., 2018*; *Pinniger, 2001*; *Palazzo et al., 2021*). To our knowledge, a comprehensive review of these pests has not yet been conducted. In this review, we aim to focus on the most significant pests threatening homes and historic buildings in Europe. Table 1 highlights the main insect species commonly found in both heritage sites and domestic residences in France. We will examine their biology, the damage they cause, and their impact on human health, specifically focusing on five major

Table 1 Insects commonly observed in both heritage sites and human residences in France.

Species	Order	Family
******Adistemia watsoni* (Wollaston, 1871)	Coleoptera	Latridiidae
*******Ahasverus advena* (Waltl, 1834)	Coleoptera	Silvanidae
*******Alphitobius diaperinus* (Panzer, 1797)	Coleoptera	Tenebrionidae
*******Alphitobius laevigatus* (Fabricius, 1781)	Coleoptera	Tenebrionidae
*****Anobium punctatum* (De Geer, 1774)	Coleoptera	Ptinidae
*****Anthrenus flavipes* (LeConte,1854)	Coleoptera	Dermestidae
*****Anthrenus museorum* (Linnaeus, 1761)	Coleoptera	Dermestidae
******Anthrenus pimpinellae* (Fabricius, 1775)	Coleoptera	Dermestidae
*****Anthrenus scrophulariae* (Linnaeus, 1758)	Coleoptera	Dermestidae
*****Anthrenus verbasci* (Linnaeus, 1767)	Coleoptera	Dermestidae
******Attagenus bifasciatus* (Olivier 1790)	Coleoptera	Dermestidae
*****Attagenus brunneus* Faldermann, 1835	Coleoptera	Dermestidae
*****Attagenus cyphonoides* Reitter, 1881	Coleoptera	Dermestidae
******Attagenus fasciatus* (Thunberg, 1795)	Coleoptera	Dermestidae
*****Attagenus pellio* (Linnaeus, 1758)	Coleoptera	Dermestidae
*****Attagenus smirnovi* (Zhantiev, 1973)	Coleoptera	Dermestidae
*****Attagenus unicolor* (Brahm 1791)	Coleoptera	Dermestidae
*****Blatta orientalis* (Linnaeus, 1758)	Dictyoptera	Blattellidae
*****Blattella germanica* (Linnaeus, 1767)	Dictyoptera	Blattelidae
******Bostrichus capucinus* (Linnaeus, 1758)	Coleoptera	Bostrichidae
*******Carpophilus hemipterus* (Linnaeus, 1758)	Coleoptera	Nitidulidae
*******Carpophilus ligneus* Murray, 1864	Coleoptera	Nitidulidae
*******Carpophilus obsoletus* Erichson, 1843	Coleoptera	adistemia
*******Cartodere constricta* (Gyllenhal, 1827)	Coleoptera	idem adistemia
*******Corticaria elongata* (Gyllenhal, 1827)	Coleoptera	Lathridiidae
*******Cryptolestes ferrugineus* (Stephens, 1831)	Coleoptera	Laemophloeidae
*******Cryptophagus cellaris* (Scopoli, 1763)	Coleoptera	Cryptophagidae
*****Ctenolespisma lineata* (Fabricius, 1775)	Zygentoma	Lepismatidae
*****Ctenolespisma longicaudatum* Escherich, 1905	Zygentoma	Lepismatidae
*******Dermestes ater* (DeGeer, 1774)	Coleoptera	Dermestidae
*******Dermestes bicolor* (Fabricius, 1781)	Coleoptera	Dermestidae
*******Dermestes carnivorus (Fabricius, 1775)*	Coleoptera	Dermestidae
******Dermestes frischii Kugelann, 1792*	Coleoptera	Dermestidae
*******Dermestes haemorrhoidalis* (Küster, 1852)	Coleoptera	Dermestidae
*******Dermestes lardarius Linnaeus, 1758*	Coleoptera	Dermestidae
*******Dermestes maculatus De Geer, 1774*	Coleoptera	Dermestidae
*******Dermestes murinus* (Linnaeus, 1758)	Coleoptera	Dermestidae
*******Dermestes mustelinus* (Erichson, 1846)	Coleoptera	Dermestidae
******Dermestes peruvianus* (Laporte de Castelnau, 1840)	Coleoptera	Dermestidae
******Dermestes undulatus* Brahm, 1790	Coleoptera	Dermestidae
*******Dienerella argus* (Reitter, 1884)	Coleoptera	Lathridiidae

(Continued)

Table 1 (continued)

Species	Order	Family
***Dinoderus minutus* (Fabricius, 1775)	Coleoptera	Bostrichidae
**Dorypteryx domestica* (Smithers, 1958)	Psocoptera	Psyllipsocidae
**Dorypteryx longipennis Smithers, 1991*	Psocoptera	Psyllipsocidae
**Ernobius mollis (Linnaeus, 1758)*	Coleoptera	Ptinidae
**Gibbium psylloides* (Czenpinski, 1778)	Coleoptera	Ptinidae
**Hexarthrum exiguum* (Boheman, 1838)	Coleoptera	Curculionidae
**Hylotrupes bajulus* (Linneaus, 1758)	Coleoptera	Cerambycidae
**Kalotermes flavicollis* (Fabricius, 1793)	Isoptera	Kalotermitidae
**Lasioderma serricorne* (Fabricius, 1792)	Coleoptera	Ptinidae
**Lepisma saccharina (Linnaeus, 1758)*	Zygentoma	Lepismatidae
**Liposcelis corrodens (Heymons, 1909)*	Psocoptera	Liposcelididae
**Liposcelis decolor (Pearman, 1925)*	Psocoptera	Liposcelididae
***Litargus balteatus* LeConte, 1856	Coleoptera	Mycetophagidae
**Lyctus brunneus (Stephens, 1830)*	Coleoptera	Bostrichidae
**Lyctus linearis (Goeze, 1777)*	Coleoptera	Bostrichidae
**Megatoma undata* (Linnaeus, 1758)	Coleoptera	Dermestidae
**Mezium affine (Boieldieu, 1856)*	Coleoptera	Ptinidae
***Necrobia ruficollis* (Fabricius, 1775)	Coleoptera	Cleridae
***Necrobia rufipes* (De Geer, 1775)	Coleoptera	Cleridae
***Necrobia rufipes* (DeGeer, 1775)	Coleoptera	Cleridae
**Nicobium castaneum (Olivier, 1790)*	Coleoptera	Ptinidae
**Niptus hololeucus (Faldermann, 1835)*	Coleoptera	Ptinidae
**Oligomerus ptilinoides (Wollaston, 1854)*	Coleoptera	Ptinidae
***Oryzaephilus mercator* (Fauvel, 1889)	Coleoptera	Silvanidae
***Oryzaephilus surinamensis* (Linnaeus, 1758)	Coleoptera	Silvanidae
***Palorus depressus* (Fabricius, 1790)	Coleoptera	Tenebrionidae
**Pentarthrum huttoni* Wollaston, 1854	Coleoptera	Curculionidae
**Phradonoma villosulum* (Dufschmid, 1825)	Coleoptera	Dermestidae
**Plodia interpunctella (Hübner, 1813)*	Lepidoptera	Pyralidae
**Priobium carpini* (Herbst, 1793)	Coleoptera	Ptinidae
**Psyllipsocus ramburii Sélys-Longchamp, 1872*	Psocoptera	Psyllipsocidae
**Ptilinus pectinicornis* (Linnaeus, 1758)	Coleoptera	Ptinidae
**Ptinus fur* Linnaeus, 1758	Coleoptera	Ptinidae
**Ptinus latro* Fabricius, 1175	Coleoptera	Ptinidae
**Ptinus variegatus* Rossi, 1792	Coleoptera	Ptinidae
**Reesa vespulae* (Milliron, 1939)	Coleoptera	Dermestidae
***Rhyzopertha dominica* (Fabricius, 1792)	Coleoptera	Bostrichidae
***Sefrania bleusei* (Pic, 1899)	Coleoptera	Dermestidae
***Silvanus bidentatus* (Linnaeus, 1792)	Coleoptera	Silvanidae
***Sitophilus oryzae* (Linnaeus, 1763)	Coleoptera	Dryophthoridae
***Sitophilus zeamais* (Motschulsky, 1855)	Coleoptera	Dryophthoridae

Table 1 (continued)

Species	Order	Family
**Stegobium paniceum* (Linnaeus, 1758)	Coleoptera	Ptinidae
***Supella longipalpa* (Fabricius, 1798)	Dictyoptera	Blatellidae
****Tenebrio molitor* Linnaeus, 1758	Coleoptera	Tenebrionidae
****Tenebrio obscurus* Fabricius, 1792	Coleoptera	Tenebrionidae
***Thermobia domestica* (Packard, 1837)	Zygentoma	Lepismatidae
**Thylodrias contractus* (Motschulsky, 1839)	Coleoptera	Dermestidae
****Thyphea stercorea* (Linnaeus, 1758)	Coleoptera	Mycetophagidae
**Tinea pellionella* (Linnaeus, 1758)	Lepidoptera	Tineidae
**Tineola bisselliella* (Hummel, 1823)	Lepidoptera	Tineidae
****Tribolium castaneum* (Herbst, 1797)	Coleoptera	Tenebrionidae
****Tribolium confusum* Jacquelin du Val, 1861	Coleoptera	Tenebrionidae
***Trichoferus holosericeus* (Rossi, 1790)	Coleoptera	Cerambycidae
***Trogium pulsatorium* (Linnaeus, 1758)	Psocoptera	Trogiidae
***Trogoderma augustum* (Solier, 1849)	Coleoptera	Dermestidae
***Trogoderma glabrum* (Herbst, 1783)	Coleoptera	Dermestidae
***Trogoderma granarium* Everts, 1898	Coleoptera	Dermestidae
***Trogoderma inclusum* LeConte, 1854	Coleoptera	Dermestidae
***Trogoderma megatomoides* Reitter, 1881	Coleoptera	Dermestidae
**Trogoderma versicolor* (Creutzer, 1799)	Coleoptera	Dermestidae
***Trogoxylon impressum* (Comolli, 1837)	Coleoptera	Bostrichidae
**Xestobium rufovillosum* (De Geer, 1774)	Coleoptera	Ptinidae

Notes:
* The most common and hazardous species.
** Species of lesser significance for the heritage domain.
*** Rarer species that may be present in heritage sites.

orders of urban insect pests: Coleoptera, Blattodea (cockroaches, termites), Lepidoptera, Zygentoma (silverfish), and Psocoptera (booklice). Additionally, we will discuss several promising methods for identifying and detecting these pests. A greater understanding of these pests will help improve pest control programmes, thus reducing threats not only to human health but also to cultural heritage and economic well-being.

SURVEY METHODOLOGY

To ensure a comprehensive, unbiased, and repeatable literature search, we conducted an extensive review on PubMed, Google Scholar, and Web of Science. Our search criteria included keywords specific to insect pests in homes and cultural heritage sites, such as "insect pests in museums," "insects in homes," "cultural heritage pests," and keywords for particular pest orders (*e.g.*, *Blattodea*, *Psocoptera*, *Coleoptera*). We also included terms related to specific environments like "historic buildings," "archives," "libraries," and "museums," with a focus on studies conducted in or relevant to Europe.

- **Search outcome:** The initial search returned 1,207 publications, from which we removed six duplicates. Titles and abstracts of the remaining 1,201 studies were reviewed,

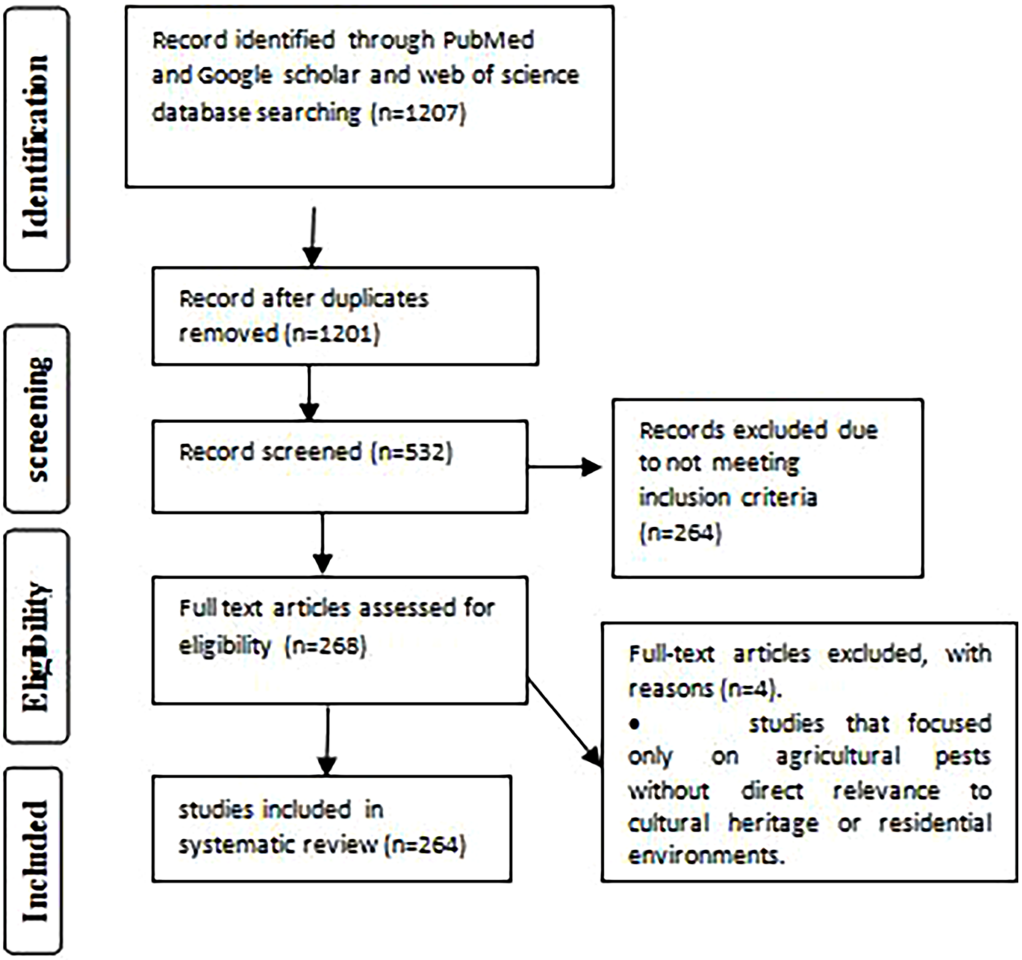

Figure 1 **Flowchart summary of the selection process.** Full-size DOI: 10.7717/peerj.18700/fig-1

excluding 675 that were not directly related or were non-original research (*e.g.*, reviews, meta-analyses).

- **In-depth screening:** Full texts of 532 studies were then evaluated for those that identified pest species and examined their impact on materials in domestic or heritage settings in Europe.
- **Final selection:** After this detailed screening, 268 studies were excluded as they either lacked European data or did not address household or cultural heritage pests specifically. Our final review comprised 33 studies directly relevant to insect pest impact on cultural heritage and home environments (Fig. 1).

Coleoptera

Coleoptera is one order of pests that can have a negative influence on cultural heritage and human life (*Strang & Kigawa, 2009*; *Brimblecombe, Jeannottat & Querner, 2023*). This order has the highest number of known species of any insect order, (*Rees & Rangsi, 2004*)

and is divided into four suborders. Almost 90% of the family and species that have an impact on human existence are in the Polyphaga suborder (*Eldridge & Edman, 2012*).

The principal beetle pests, which damage stored items, timber in buildings, packing cases, and furniture, belong to the families Ptinidae, Cerambycidae, Lyctidae, Curculionidae, Dermestidae, and Bostrychidae (*Toriti, Durand & Fohrer, 2021*). Species such as *Attagenus unicolor* have been recognised as dangerous museum invaders. According to Back and Cotton, this insect attacks a wide range of animals and feeds on grain products (*Su & Scheffrahn, 1990*). Other species, such as *Lyctus brunneus*, a tropical species that was first discovered in Venice in 1972, are known for their high reproductive rate (60–70 eggs per female) and the ability to spread rapidly (*Manachini, Billeci & Palla, 2013*). *Stegobium paniceum*, commonly known as biscuit beetles or tobacco beetles (*Lasioderma serricorne*) (*Wu, Thiers & Pfister, 2004*), consume a variety of dried plant products, including biological specimens found in museum collections (*Cao et al., 2022*).

Anobium punctatum, known as the bookworm, woodworm, or common furniture beetle (*Hagstrum, 2017*), is the most common and damaging anobiid beetle in northern Europe and the UK (*Pinniger & Child, 1996*). It has been known to damage museums, cathedrals, castles, and other historical structures and grows in practically all native wild and cultivated wood species, as well as in a few tropical kinds of wood (*Paul, Prozell & Schöller, 2007*).

The most frequently observed species in both stored product and heritage buildings are classified into three categories: primary, secondary, and tertiary pests (*Pinniger & Lauder, 2018*; *Hagstrum, 2017*). The main families that have an impact on homes and historic buildings are listed below (Table 2).

Bostrichidae

The lesser grain borer (*Rhyzopertha dominica*) belongs to the Bostrichidae family, which includes over 700 species, many of them wood borers. Some bostrichid beetles, including the lesser grain borer, can reduce bamboo and sapwood timber to a powdery frass. This causes significant economic losses in the forestry and lumber industries. The larvae typically inhabit the sapwood and cambium of dead, injured, or newly cut and stored branches and trunks, facilitating the spread of invasive species across countries. In many parts of the world, particularly tropical and subtropical regions, *Rhyzopertha dominica* is also a major pest of grain crops. This cosmopolitan, polyphagous insect pest can cause huge economic losses in stored goods (*Edde, 2012*; *Ortega et al., 2021*; *Shah et al., 2021*). This species has been found in botanical remains kept in the Museum of Liverpool in the UK (*Panagiotakopulu, 1998*).

Powderpost beetles are named after the effect that these bostrichid beetle larvae and adults can have on bamboo and sapwood timber, often turning it into powdery frass. As a result, the forestry industry and lumber-dependent businesses have experienced enormous economic losses (*Liu, Leavengood & Bernal, 2022*). Like the lesser grain borer, powderpost larvae live in the sapwood and cambium of dead, injured, or newly cut and stored branches and trunks, which has aided the spread of foreign species from one country to another (*Toriti, Durand & Fohrer, 2021*).

Table 2 Coleoptera species commonly observed in both heritage sites and human residences.

Species	Distribution	Damage
Mezium affine	Europe, North Africa.	House, warehouses, granaries, decaying animal and vegetable debris, dead insects.
Mezium americanum	Cosmopolitan.	Dwellings, dried animal products, warehouses, mills, infested cayenne pepper, opium, grain, obacco.
Gibbium psylloides	Cosmopolitan	Houses, hotels, warehouses, mills, granaries, stored seeds, woollen materials
Gibbium boieldieui	Europe, Persia, Russia, Malay archipelago	Houses feeding on bread, cheese, and moulds
Gibbium aequinoctiale	Nearly cosmopolitan	Houses feeding on bread, cheese, and moulds
Sphaericus pinguis	South Europe, North Africa, California	Herbarium pest living in red pepper
Epauloecus unicolor	Europe, Canada Transcaucasia.	Houses, Warehouses, old wood, birds' nests
Niptus hololeucus	Nearly cosmopolitan but absent in the tropics.	Houses, Warehouses, dried organic materials, dead insects, clothing soiled by grease.
Trigonogenius globulus	Europe, Africa, North and South America, Tasmania	Houses, warehouses, granaries, and in cotton, flour, and corn mills
Pseudeurostus hilleri	Japan, Great Britain, Canada	Warehouses, granaries
Ptinus (Cyphoderes) japonicus	Japan, India, Russia	Infests and damages flour made of *Amorphophallus koniac*, used for food in Japan
Ptinus (Cyphoderes) raptor	Europe, Russia, Canada, USA	Stored grain in warehouses
Ptinus (Bruchoptinus) rufipes	Europe	Dead wood, a pest of stored products
Ptinus (Tectoptinus) exulans	Europe, Australia, Asia, Tasmania	Pest of stored products
Ptinus (Tectoptinus) tectus	Cosmopolitan	Houses, granaries, warehouses, dried organic materials, dried leaves, and flowers,
Ptinus hirtellus	Cosmopolitan	Scavengers damaging books, feathers, hides, dried mushrooms, drugs, and roots, stored products (sugar, dried fruit)
Ptinus latro	Nearly cosmopolitan	Houses, warehouses, stored products
Ptinus (Ptinus) fur	Cosmopolitan	Omnivorous feeder, dried and decaying animal and vegetable matter, feathers and animal hides, stored products
Ptinus pusillus	Europe	Stored products
Ptinus subpilosus	Europe	Houses, wood, and ants' nests
Ptinus bicinctus	Europe, North Africa, North America	Warehouses, dwellings, old wooden items, stored products
Ptinus villiger	Europe, Asia, and North America.	Houses, warehouses, stored products.

The most common pest species, *Dinoderus minutus*, has a worldwide spread, poses a danger to maize crops, and attacks bamboo-based structures and structures. Breeding sites include rattan goods and wooden container crates (*Liu, Leavengood & Bernal, 2022*; *Majka, 2007*).

Lyctus linearis and *Lyctus brunneus* are worldwide xylophagous beetles that attack wood. They damage furniture, woodwork, and other materials. The French entomologist Pierre Lesne first discovered these species in a collection of museum woodwork during his research (*Lesne, 1922*, *1910*).

Another significant species that damages furniture is *Bostrichus capucinus*, which can pierce lead plates with their powerful mandibles (*Toriti, Durand & Fohrer, 2021*).

Cerambycidae (longhorn beetles or Capricorn beetles)

According to the literature, the family Cerambycidae (longhorn beetles) or Capricorn beetles includes some of the world's most destructive xylophagous species (*Brockerhoff et al., 2006*). From an economic standpoint, it is one of the largest groups of insects in the world, affecting forests, timber products, shade trees, and fruit and nut trees (*Kariyanna, Mohan & Gupta, 2017*). Most damage occurs in the larval stages and affects both softwoods and hardwoods (*Raje et al., 2012*). *Hylotrupes bajulus* is one of the principal species in this family and is thought to be responsible for significant economic losses in wood and wood products (*Yalcin et al., 2020*). This species poses a threat to historical items, attacking any wooden furniture including antique clocks and carved wooden furniture, and it has been demonstrated that it prefers wood kept in long-term storage (*Kariyanna, Mohan & Gupta, 2017*; *Yalcin et al., 2020*).

Silvanidae (saw-toothed beetle)

Oryzaephilus surinamensis is a serious pest affecting stored goods (*Vendl, Stejskal & Aulicky, 2019*) and is an invader of packaged consumer foods worldwide. It enters through improperly sealed openings or tears in packaging and has a significant negative economic impact (*Gharsan et al., 2018*, *2022*). It is considered a very serious devastator, as it poses a threat to dates and other dried fruits (*Hashem, Khalifa & Ahmed, 2021*). Its rapid reproduction and profusion can cause it to invade many healthy spaces, such as packaging and empty stored bottles, leading to their presence when these are filled (Fig. 2).

Curculionidae (weevils)

This family includes the most destructive tree-killing bark beetles in Europe, including *Scolytus multistriatus, Scolytus rugulosus*, and *Ips typographus*. Beetles from the Cossoninae subfamily are a specialist group that generally develops in fresh to rotting wood. Other species include *Amaurorhinus brewickianus, Pselactus spadix* and *Pseudophloeophagus truncorum* (*Liotta, 2015*; *Skuhrovec, Hlaváč & Batelka, 2017*). Through their feeding activities, these species were responsible for the separation of certain artefact components on display at the museum, causing significant ecological and economic damage (*Powell et al., 2021*; *Jeger et al., 2017*; *Tanin, Kandasamy & Krokene, 2021*).

The most destructive and widespread species, *Pentarthrum huttoni*, is found in historic buildings and human dwellings. It was first discovered in Austria and was responsible for the irreversible disintegration of 18th century wooden coffins (*Halmschlager et al., 2007*; *Domenico, 2012*). *Hexarthrum exiguum* has been identified as a harmful species which originates from the external environment and infests historical goods made of wood (*Ungurean, 2012*). It is known as the "pit-prop beetle" in Central Europe because it damages wet wood, primarily in mines but also in homes (*Cebeci, Hellrigl & Whitehead, 2011*). Species such as *Sitophilus granarius*, *Sitophilus oryzae*, and *Sitophilus zeamais*

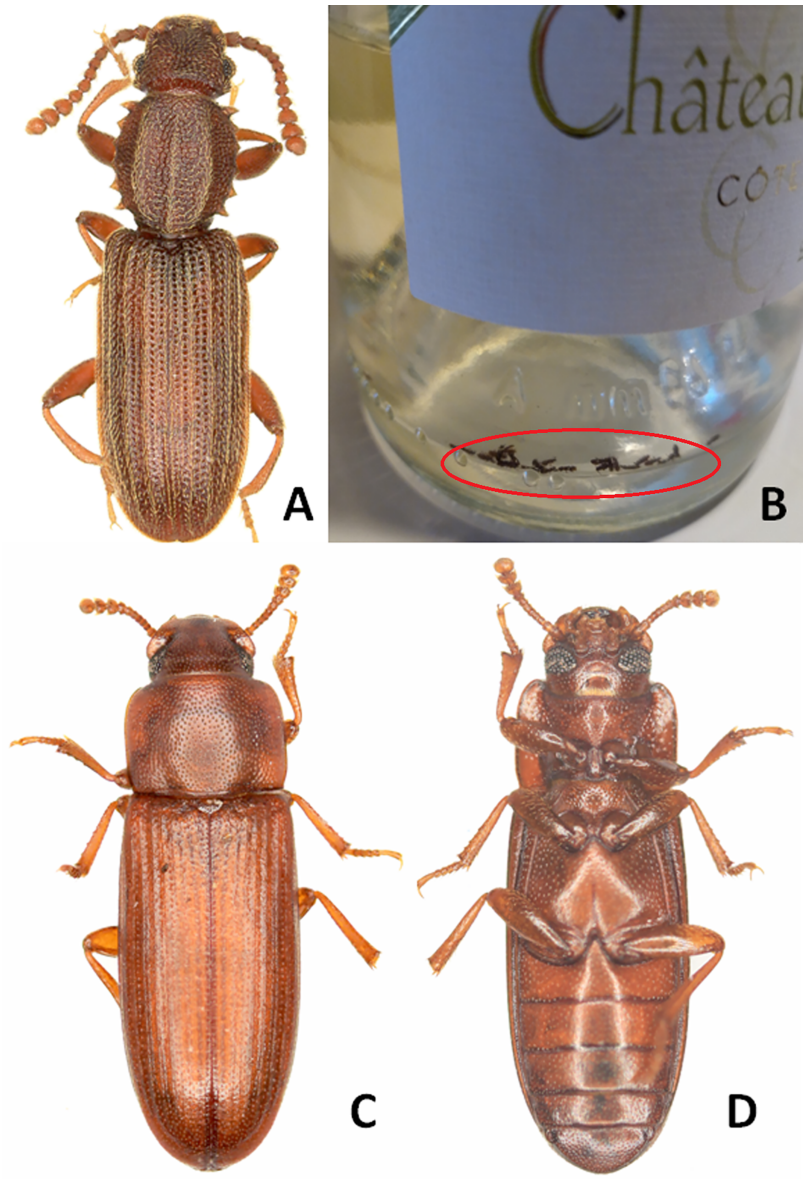

Figure 2 The Coleoptera species *Oryzaephilus surinamensis* and *Tribolium castaneum*. Coleoptera (A) dorsal view of adult *Oryzaephilus surinamensis*, (B) red circle indicating an *Oryzaephilus surinamensis* trapped inside a bottle, (C) dorsal view of adult *Tribolium castaneum*, (D) ventral view of adult *Tribolium castaneum*.
Full-size DOI: 10.7717/peerj.18700/fig-2

colonise and destroy grain, and inflict significant losses on a global scale (*Hagstrum, 2017*). *Sitophilus granarius* is the most frequently discovered species in archaeological contexts and may be found in settings ranging from tiny rural warehouses to huge storage silos (*Lemic et al., 2020*; *Pécréaux, 2008*).

Ptinidae

The Ptinidae family includes both xylophagous insects, which feed on wood, and polyphagous insects that are pests of stored goods (*Toriti, Durand & Fohrer, 2021*). Many species previously classified in the Anobiidae family are now included in the Ptinidae

Figure 3 The Coleoptera species *Anobium punctatum* and *Attagenus smirnovi*. (A) Woodborers (Coleoptera: Ptinidae, formerly Anobiidae) adult *Anobium punctatum*, (B) adult *Attagenus smirnovi*.
Full-size DOI: 10.7717/peerj.18700/fig-3

family. Some larvae contribute to the deterioration of organic plant and animal matter, with certain species consuming dry excrement or feeding on animal corpses. For instance, *Ptinus sexpunctatus*, *Ptinus pyrenaeus*, and *Ptinus tectus* can be found in the nests of social hymenopterans, where they feed on exuviae and organic waste.

Some species of Ptinidae larvae lead to the deterioration of organic plant and animal matter. While some species consume dry excrement, others feed on animal corpses. *Ptinus sexpunctatus*, *Ptinus pyrenaeus*, and *Ptinus tectus* are examples of larvae that can be found in the nests of social hymenopterans, where they feed on their exuviae and organic waste (*Calmont, 2016*).

In 1941, the Department of Entomology at the British Museum highlighted 21 species of Ptinidae identified as pests. The majority of them destroy stored goods of all kinds and belong to two sub-families, Gibbinae and Ptininae, represented in the table below (*Hinton, 1941*). Woodborers such as *Anobium punctatum* (Coleoptera: Ptinidae, formerly Anobiidae), a widespread species, were common in furniture and historic buildings in the past, but with the rise of modern housing, they are now frequently found in museums and historic buildings. Wood-boring beetles have been found in wooden shipping crates and wooden pallets used to transport and protect works of art, which has resulted in these works becoming infested with these pests and contaminating museums (Fig. 3). Three cases of infestations of newly manufactured picture frames in Austria between 2010 and 2015 and wooden pallets were all associated with the spread of various wood-boring beetles (*Child & Pinniger, 2014*; *Wang, 2021*; *Biebl & Querner, 2021*). This pest is responsible for significant financial losses due to the irreversibly damage it causes (*Paul, Prozell & Schöller, 2007*; *Auer, Opitz & Kassel, 2021*). *Xestobium rufovillosum*, known as the death-watch beetle, is the largest species in terms of size. The larvae prefer aged oak timber rather than softwood and can damage wooden objects in museums and libraries if exposed to fungal decay (*Campbell & Bryant, 1940*; *Crous et al., 2020*; *Campbell, 1941*; *Toriti, Durand & Fohrer, 2022*). Infestation is favoured when humidity is high. In humid environments,

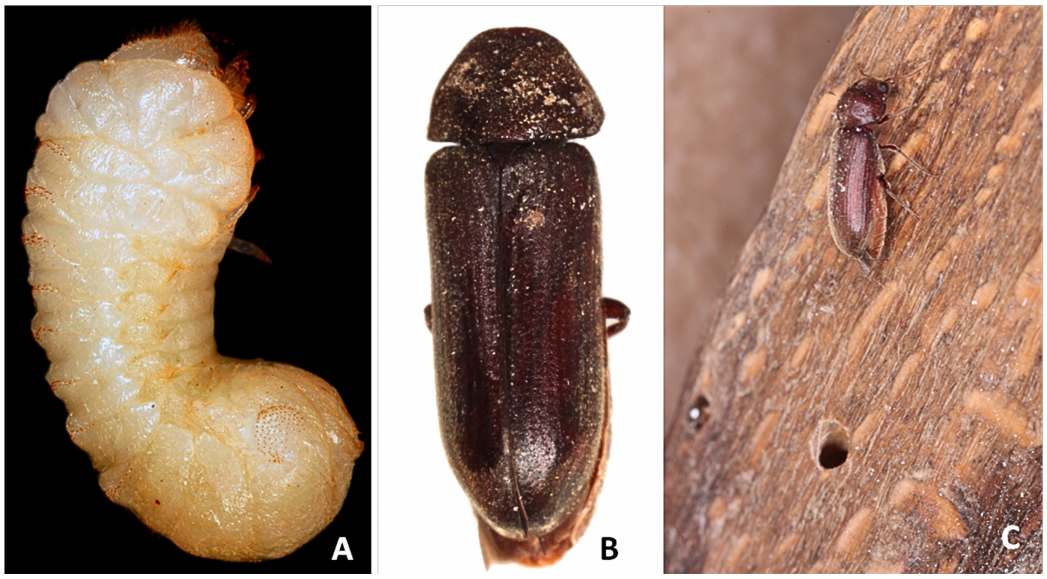

Figure 4 Coleoptera. C Wood-boring beetle (Coleoptera): *Oligomerus ptilinoides* larvae (A), adult (B), *Oligomerus ptilinoides* adult in a natural environment, showcasing the damage caused by larvae through small, irregularly shaped holes in the surface of wooden furniture (C).
Full-size DOI: 10.7717/peerj.18700/fig-4

fungus can soften the wood, which allows insect larvae to more easily tunnel through the wood while feeding on cellulose and hemicellulose (*Richards & Brimblecombe, 2022*). *Oligomerus ptilinoides*, a species of beetle belonging to the Anobiidae family and native to the Mediterranean region, is renowned for its destructive impact on wood in some southern European countries (Fig. 4). It is particularly notorious for the extensive damage it inflicts on objects made from hardwood, such as furniture and works of art (*Halperin, 1992*).

Recently, *Gibbium psylloides*, which belongs to the Ptinidae family, was identified during a survey to determine the biodiversity of insect pests that infest the manuscript library of the Coptic Museum in Egypt (*Abu El-Hassan et al., 2021*). *Lasioderma serricorne* (a polyphagous insect), known as the "cigarette beetle", is a serious pest of museums, books, and dried plants, in addition to being a pest of tobacco storage. Because of the harm it can do to dried herbarium specimens, this beetle is known as the "herbarium beetle" in hotter countries (*Edde, 2019*; *Guarino et al., 2021*). Among the polyphagous insects, *Mezium affine* is known as the "spider beetle" because of its round body shape. The larvae feed on dried meat, dried mushrooms, seeds, wool, hair, feathers, leather, book bindings, insect collections, books, and all kinds of dried animal and plant specimens, leading to their classification among the insects that threaten museums (*Dogruer, 2022*). *Nicobium castaneum* poses a threat to all types of wood products, including composite wood, and typically destroys historical artefacts, eating old documents as well as every kind of paper, cardboard, parchment, and leather (*Shah et al., 2021*). *Stegobium paniceum* (a polyphagous insect), is known as the "drugstore beetle" and damages dry plants, paper pulp, and starch-rich cardboard. It usually feeds on

the bindings of old books that have been coated with starch glue, leaving tunnels (*Cao et al., 2022*; *Abdelghany et al., 2010*; *Shah et al., 2021*).

Dermestidae (hide and carpet beetles)

The term "dermestid" comes from the Greek term "*dermestes*", meaning "skin-eater". This family contains over 1,800 named species (*Busvine, 2013*). Certain species within this family are of significant economic and cultural concern due to their pest-like behaviour, as they can spread easily through global trade (*Querner et al., 2013*; *Bradshaw et al., 2016*). These beetles are found in a variety of biological settings, including human residences, animal carcasses, and bird and spider nests. Recently, they have become prevalent pests in the rapidly growing pet food sector in many wealthy countries (*Zeng et al., 2021*). Among the species of this family that are considered as pests of historic buildings and homes, are species from the genera *Anthrenus*, the larvae of which are harmful to different commodities of natural origin. Species from the genera *Anthrenus*, include *Anthrenus flavipes*, also known as the "carpet beetle", a common pest that can cause damage to museums and households (*Hava, 2022*; *Kumar et al., 2013*). It damages textiles, clothing, and items made of animal origin, such as wool, fur, feathers, and hide, in addition to carpets (*Kumar et al., 2013*). *Anthrenus verbasci* is a cosmopolitan species known as the "museum beetle" and has been detected on old books and ethnographic textiles (Fig. 5) (*Pradhan, 1948*; *Antonie & Teodorescu, 2009*; *Peace et al., 2022*). Also known as the "varied carpet beetle", it infests items such as carpets, woollen materials, silks, hides, furs, feathers, hair, horn, cereals, red peppers, fishmeal, and any processed animal or plant food. In common with other carpet beetles, this species will feed on cotton, linen, and synthetic fibres if they are contaminated with human excretions (blood, skin, hair) (*Faheem & Abduraheem, 2019*). Most species of the genera *Attagenus* spread through infested bird nests, rodent carcasses, and dead birds (*Querner, 2015*), such as *Attagenus pellio*, known as the "two-spot carpet beetle" (*Bergmann-Hug, Furrer & Helbling, 2007*). Other significant pests of organic artefacts in European museums are *Attagenus smirnovi*, also known as "vodka beetles" or "carpet beetles" (Fig. 6) (*Hansen et al., 2012*; *Schmidt et al., 2023*). *Attagenus unicolor*, known as the "black carpet beetle" is a household pest unique in its ability to digest complex proteins, and is widely recognised as a serious economic pest threatening stored products and museum collections (*Keefe & Lei, 2021*; *Zhou et al., 2022*).

Species from the *Dermestes* genus (Coleoptera: Dermestidae) can be serious pests threatening stored animal products, such as food, silkworm cocoons, leather and other textile items, and museum collections. Both the adult and larval stages are scavengers that favour dry, protein-rich organic matter (*Gharsan et al., 2022*; *Martín-Vega et al., 2017*; *Kadej et al., 2022*). The genus includes species that are of forensic interest, such as *Dermestes haemorrhoidalis, Dermestes ater, Dermestes frischii*, and *Dermestes lardarius* (*Kadej et al., 2022*; *Magni et al., 2015*; *Charabidze et al., 2014*).

The *Trogoderma* genus, containing approximately 130 described species is widely distributed (*Castalanelli et al., 2012*). Among these species is the khapra beetle, *Trogoderma granarium*, which originated from India (*Busvine, 2013*). This species is extremely destructive and is classified as a quarantine pest in the United States. Another

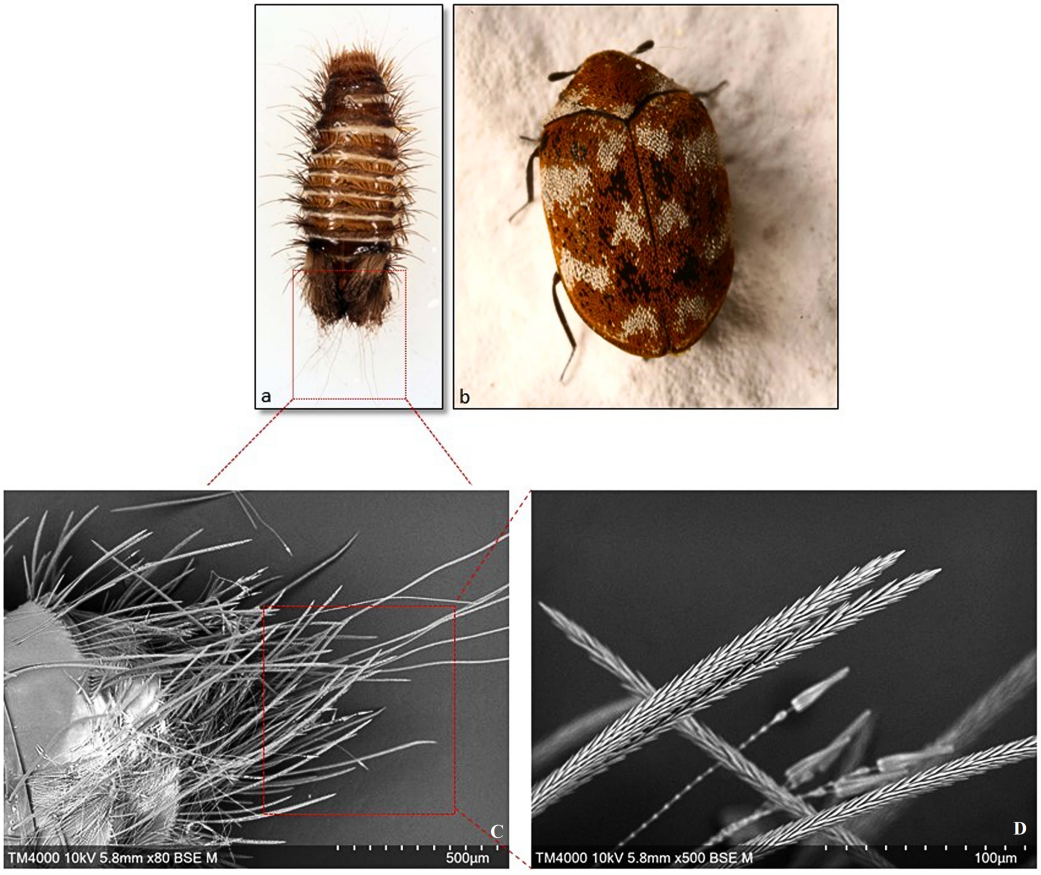

Figure 5 Carpet beetle (Coleoptera) *Anthrenus verbasci*. Carpet beetle (Coleoptera) *Anthrenus verbasci* larvae (A), adult (B), electron microscope demonstrations of larval hairs (setae) look like arrows due to their pointed and barbed appearance (C, D). Full-size DOI: 10.7717/peerj.18700/fig-5

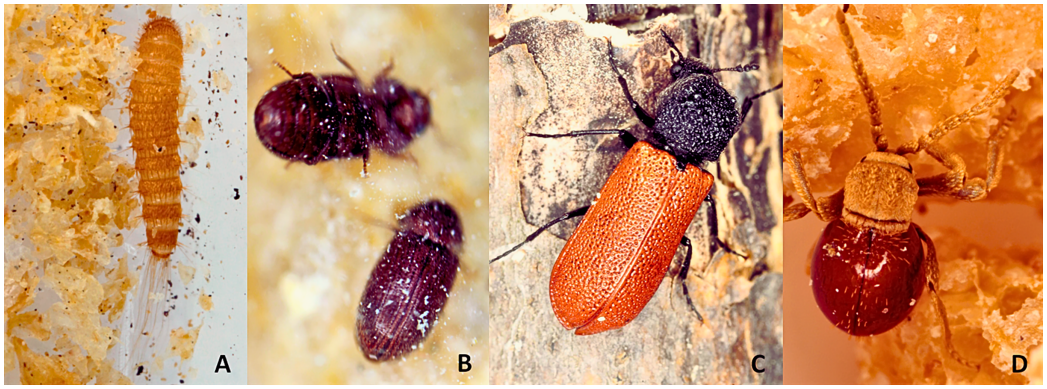

Figure 6 Different Coleoptera species. (A) Larvae of carpet beetles *Attagenus* sp, (B) ventral and dorsal views of the adult drugstore veetle, *Stegobium paniceum*, (C) adult *Bostrychus capucinus*, (D) adult brown carpet beetle, *Mezium affine*, observed in its natural environment.
Full-size DOI: 10.7717/peerj.18700/fig-6

significant pest in this genus is the warehouse beetle (*Trogoderma variabile*), a common and destructive insect found in stored products. It is highly fertile, a strong flyer, and often found in processing facilities and storage warehouses. (*Gerken et al., 2021*) Additionally, *Trogoderma angustum* is a notable pest of museums and historic houses. Its larvae are exceptionally polyphagous and are capable of developing on a wide range of plant, grain, and animal-based products (*Holloway & Sparks, 2023*).

Biology of coleopotera

The biology of beetles is diverse, due to the high number of species, although there are many common characteristics. Anatomically adult beetles (Coleoptera) have four stiffened wings known as "elytra" covering the abdomen and separating them from other insects (*Noh et al., 2016*). For some families, such as blister and false blister beetles, the body and elytra are soft. The head contains the mouthparts that are adapted for biting or chewing (*Busvine, 2013*). There are four stages in the lifecycle of beetles, and complete metamorphosis begins with the egg, and moves through the larval and pupal stages before finally becoming, adults (*Mullen & Durden, 2018*).

Eggs are placed individually or in clusters on or in soil, living or dead plant debris, textiles, water, carrion, and, in rare cases, living animals. They hatch as vigorous larvae containing simple eyes (ocelli) and chewing, mandibulate mouthparts, and an abdomen segmented into between eight and ten parts. Most beetle larvae moult at least three times before becoming pupae (*Eldridge & Edman, 2012*). Beetle larvae are often responsible for the most damage to different materials (*Mullen & Durden, 2018*).

In the UK, for example, adult *Anobium punctatum* beetles emerge between April and July and survive for 20–30 days. Females deposit their eggs in rough wood, end grain, cracks and crevices, as well as old flight holes. The eggs hatch within 15–25 days. Excreta (frass) is abundant in the larval tunnels, and has a gritty texture and barley-grain form. When the larvae are fully developed, the pupal chamber expands. After 2 to 3 weeks, depending on the family to which it belongs, the adults emerge, leaving a distinctive circular exit hole in the case of Ptinidae family and an oval-shaped hole in the case of the Cerambycidae family (*Child & Pinniger, 2014*).

Damage to and impact on human health

In addition to the significant economic losses that affect a wide range of products, buildings and industry (*Hasan et al., 2007*; *Shah et al., 2021*; *Jung et al., 2020*), these pests also affect human health. Coleoptera do not threaten human life, but some beetle species may have an impact on human health, such as the beetles of genera *Anthrenus, Attagenus, Dermestes*, and *Trogoderma* known as "carpet beetles" which can cause a cutaneous pruritic papulovesicular reaction due to the hairs (hastae) on the larval surface, which can lead to an allergic effect (*Gumina & Yan, 2021*; *Ahmed et al., 1981*). In Malaysia, a case of Cantharisis intoxication of a 1-year-old infant was thought to be due to *Lasioderma serricorne* larvae (*Mokhtar et al., 2016*). The dermestid beetle is known to infest human remains and can cause damage to bones and tissue (*Kadej et al., 2022*). Other cases of allergies in wool workers and museum staff have been reported as being caused by

dermestid beetles (*Bergmann-Hug, Furrer & Helbling, 2007*). One study has shown that Dermestids can produce chemical allergens (*Zeng et al., 2021*). Moreover, beetles such as *Anobium punctatum* play host to *Pyemotes ventricosus* mites, small arthropods that are tissue-juice feeders responsible for intensely pruritic erythematous maculopapular lesions with central micropustules (*Neumayr & Kuenzli, 2019*; *Hanks et al., 1992*; *Darles et al., 2013*; *Giudice et al., 2008*). Where the volume of *Pyemotes* exceeds the available supply of food, they have been known to occasionally bite mammals, including humans, causing dermatitis followed by a "comet sign" lymphangitis, as in the case of one Caucasian woman (*Laghi et al., 2021*; *Berenger & Parola, 2023*).

Some research suggests the possibility of isolating probiotic bacteria from the faeces of storage food insects such as *Tribolium castaneum*, and using it as a model system for screening (*Grau, Vilcinskas & Joop, 2017*).

Beetles can have a profound impact on human food supplies. One of the major concerns about them is their ability to attack grain reserves, leading to potential famine, particularly in communities which are heavily dependent on grains as their main source of sustenance (*Fornari et al., 2013*; *Yardim et al., 2006*; *Leidemer et al., 2022*). When they infest stored grains, they consume and contaminate the food, resulting in substantial crop losses and reducing the food available for human consumption. Moreover, the damage caused by beetles can compromise the quality and nutritional value of the grains, making them unsuitable for human consumption even if they are not entirely consumed (*Stathas et al., 2023*).

Blattodea

The Blattodea order includes both termites and cockroaches. Their existence goes back more than 300 million years (*Gondhalekar et al., 2021*), with more than 7,000 species of Blattodea (*Beccaloni & Eggleton, 2013*), including 3,015 species of termites and around 4,700 species of cockroaches (*Guzman & Vilcinskas, 2020*; *Lertlumnaphakul et al., 2022*; *Beccaloni, 2023*). Termites evolved from "wood-eating cockroaches" (*Bignell, 2018*).

Cockroaches are classified into several families, with some sources listing up to nine distinct families *Hashemi-Aghdam & Oshaghi (2015)* including the most primitive family, Cryptocercidae (*Huber, 1976*), which shares several important traits with termites (*Djernæs, Klass & Eggleton, 2015*) and contains a worldwide xylophagous species with fewer than ten species (*Burnside, Smith & Kambhampati, 1999*; *Hossain & Kambhampati, 2001*). Two other families are the Blattidae family, with more than 650 species and the Blattellidae family, with almost 1,000 species (*Qiu et al., 2020*). Most species have a preference for inhabiting warm tropical and subtropical zones (*Beccaloni, 2023*). The Polyphagidae family includes the smallest outdoor wood cockroach.

Cockroaches are one of the most common insects, with a high presence in cities. One percent of cockroaches, about 40 species, are considered to be pests (*Tang et al., 2019*). Four to five species are significant as pests on a worldwide scale, based on their global distribution, significant economic impact, and potential medical significance. The remaining species are minor pests or have only local significance (*Resh & Carde, 2009*). The most common significant cockroach pests include *Blattella germanica*, or the German

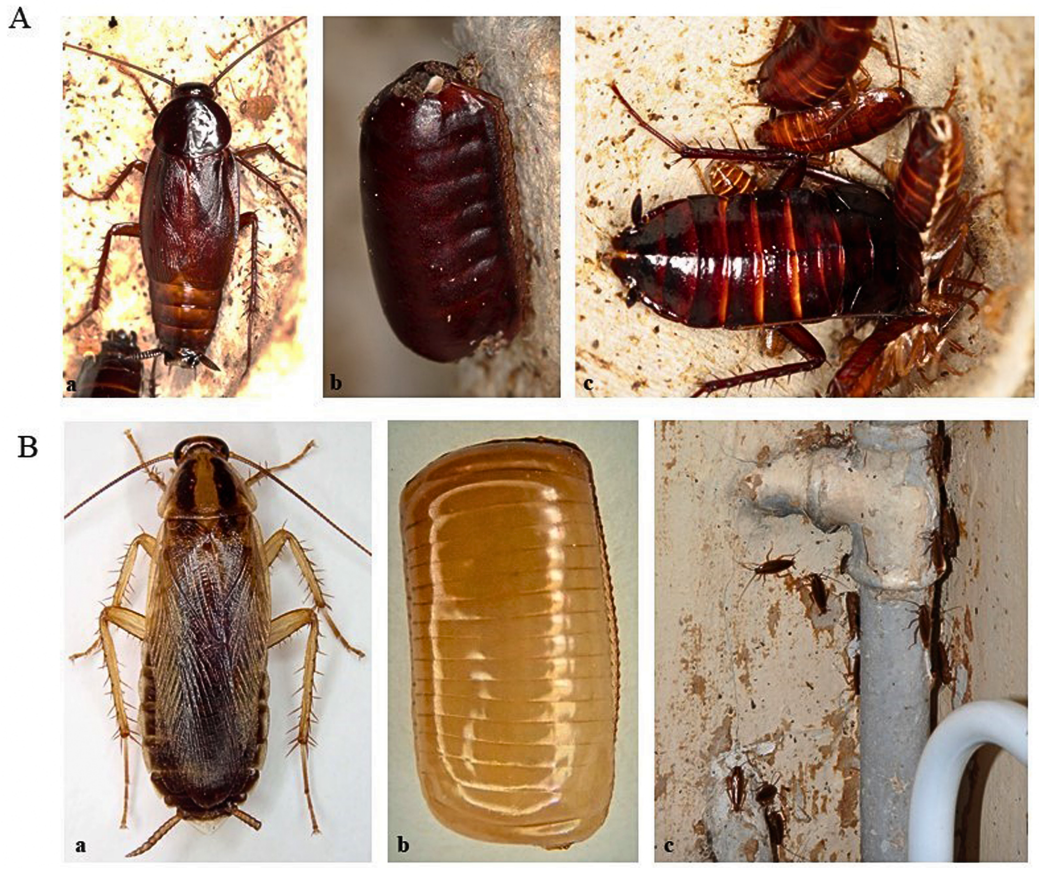

Figure 7 Blattodea species. Blattodea (Aa) adult *Blatta orientalis*, (Ab) ootheca containing the eggs of *Blatta orientalis*, (Ac) *Blatta orientalis* observed in its natural habitat. (Ba) adult *Blattella germanica*, (Bb) ootheca containing the eggs of *Blattella germanica*, (Bc) *Blattella germanica* observed near water canal conduits in its natural habitat. Full-size DOI: 10.7717/peerj.18700/fig-7

cockroach, which has been classified as a museum pest as a result of the damage it causes to museum artefacts, representing an example of the distinctive "herding" social structure that cockroaches have *Webb et al. (1994)*. Transportation and international trade have favoured the spread of the German cockroach and it is now widespread throughout the world (*Alexander, Newton & Crowe, 1991*). It is often observed in kitchens and bathrooms (*Wang et al., 2019*). The *Periplaneta americana* cockroach, known as the American cockroach, is a tropical species that can be found around the world, particularly in ports (*Porusia, Ratni & Dhesi, 2020*). This species is found mostly in the basements and ground floors of buildings (Fig. 7). A comparative study between museums in Southeast Asia and North America revealed that this species is more commonly found in Asia than in America. In Asia it is known to feed on starchy materials, sugary or fermented foods, as well as leather and parchment (*Lihoreau, Costa & Rivault, 2012*; *Rust et al., 1996*). *Supella longipalpa*, known as the brown-banded cockroach, is a domestic cockroaches that is spreading worldwide and has recently been found in buildings including hospitals, especially in urban areas. It is also referred to as the furniture cockroach (*Rust et al., 1996*; *Nasirian, 2016*). Research suggests that it has been a peridomestic pest for thousands of

years (*Tsai & Chi, 2007*). *Blatta orientalis* or the Oriental cockroach represents the biggest cockroach pest in the United Kingdom. It lives in households and industrial buildings and has spread throughout the world (*Bell, Marris & Edwards, 1998*). These species have been classified in third place among common pests in textile museums (*Singh, Sharma & Fatima, 2020*). Wood cockroaches include many species from the genera *Parcoblatta*, commonly found in the United States and other regions (*Horn & Hanula, 2002*). They consume and need a lot of moisture to survive, and are thus generally found among leaf debris and rotting wood. Wood cockroaches are occasionally found in moist basements, garages, woodsheds, and on decks under trees (*Dellinger & Dary, 2021*).

Termites are small and can be white, brown, or black. Commonly known as "white ants", with four wings of equal size, hence the name Isoptera from the Greek "isos" meaning "equal" and "pteron" meaning "wing" (*Hasnaoui et al., 2022*). termites have an almost worldwide distribution (*Krishna et al., 2013*). There are three main types of termites according to their preferred habitat: damp wood termites, which live in extremely moist wood but do not require mud or soil to survive, drywood termites, which prefer dry wood but do not require a close proximity to soil, and subterranean termites, which prefer to eat soft woods (*Nunes et al., 2005*). These are classified as posing the most serious problems to cultural wooden artefacts (*Oh & Lee, 2014*).

Drywood termites as well as subterranean termites, are frequently found in museums in colder regions, and any of them can seriously harm priceless artefacts (*Verma, Sharma & Prasad, 2009*; *Evans, Forschler & Grace, 2013*). In Australia, subterranean termites represent a major threat to the house building industry, due to their capability to damage the contents, fabric, and other materials used in the building of any type of house, including wood. Subterranean termites have been compared to an advanced cancer; once discovered it is too late to repair the destroyed structure (*Reid, 2009*). There are 28 species of termites around the globe that are regarded as invasive. According to the literature, all pest species are wood-eating, nest in food stuffs, and have a fast reproductive cycle. Most species belong to the Kalotermitidae and Rhinotermitidae families (*Evans, Forschler & Grace, 2013*). In South America, termites have been reported as structural or agricultural pests causing major damage (*Constantino, 2002*).

In Indonesia, historical buildings and cultural items are frequently infested by two termite species: *Coptotermes gestroi* and *Nasutitermes matangensis* (*Novita et al., 2020*). The *Reticulitermes* species is widespread throughout the world and six species are the most prevalent in Europe. These are *R. santonensis* in western France, *R. grassei* in southwestern France, northwestern and southern Spain, and Portugal, *R. banyulensis* in northeastern Spain, the central area of the Iberian Peninsula, and southwestern France, *R. balkanensis* in the Balkans, and *R. santonensis* in northern Italy and southeastern France (*Clément et al., 2001*). The only two termite species that were known to exist in Italy prior to the end of the 20th century were *Reticulitermes lucifugus* and *Kalotermes flavicollis*. Recently, the first report of *Reticulitermes lucifugus corsicus* was made in northern Italy (*Dutto, Ghesini & Marini, 2018*).

Biology of Blattodea

Termites and cockroaches are both part of the same order of insects known as Blattodea. While they may look very different on the surface, they share many similarities in terms of their biology and behaviour (*Lihoreau, Costa & Rivault, 2012*), both being hemimetabolous insects (*Inward, Beccaloni & Eggleton, 2007*). Their development cycle consists of several stages, including the egg, nymph, and adult stages. Females are ovoviviparous (*McGavin, Davranoglou & Lewington, 2023*).

Cockroaches have a varied diet and are omnivorous scavengers, eating many organic decaying materials, such as birds. Most species have smooth, flattened bodies that enable them to fit into small spaces, and they tend to live in crevices (*McGavin, Davranoglou & Lewington, 2023*). After adult cockroaches mate, the female lays an average of between five and 40 eggs, depending on the species of cockroach. The eggs are covered with an ootheca, a protective egg case (*Rust & Su, 2012*). The female deposits the case in a secret location and uses her saliva to adhere it to a surface. Within a month, immature cockroaches emerge in warm environments. Cockroach juveniles moult between seven and eight times before they reach adulthood (*Perrott & Miller, 2010*; *Guthrie & Tindall, 1968*; *Tanaka & Uemura, 1996*). The time for a nymph to reach the adult stage depends on the species, with an average of between 126 and 365 days, when all the conditions for development are met (*Gondhalekar et al., 2021*).

Both nymph and adult cockroaches have a mouth part containing strong toothed mandibles which are well developed for biting and chewing. In most cases, the adults have two pair of wings known as the "tegmina" (*Eldridge & Edman, 2012*).

Termite development includes an incomplete metamorphosis within castes, including nymphs, pseudergates, workers, soldiers, and several types of reproductive termites. Before becoming productive workers, nymphs hatch from eggs and moult at least three times (*Resh & Carde, 2009*; *Bouillon & Mathot, 1965*; *Lauff, 2004*).

Damage to and impact on human health

Termites and cockroaches are related to each other within the Blattodea order. Many species are among the top decomposers of dead wood and pests on the planet. They are valued for their ecological and economic contributions both locally and internationally. They are crucial to the health of many ecosystems, and the decomposition of dead wood has measurable effects on the climate (*Inward, Beccaloni & Eggleton, 2007*; *Evangelista et al., 2019*).

Less than one percent of cockroaches species are regarded as pests (*Noda et al., 2020*), because of their invasive behaviour toward homes, buildings, and other environments, infesting food, clothing, and the surfaces they crawl on. According to recent research, it is believed that cockroaches and humans started living together when people began building dwellings (*Obata, Sano & Nishizono, 2022*). Their presence can have a significant economic impact on properties and communities. While the exact financial cost of these infestations is difficult to assess, there are several ways in which they can affect property values and local economies (*Brune & Dietrich, 2015*).

Cockroaches may be implicated in the spread of nosocomial infections, which are the main causes of morbidity in immunocompromised patients (*Colombo & Guimarães, 2003*; *Fotedar & Banerjee, 1992*). Several recent studies have demonstrated the capacity of cockroaches to transmit fungi such as *Candida spp., Aspergillus spp.* (*Lemos et al., 2006*; *Nasirian, 2017*), and bacteria including *Salmonella, E. coli*, *Klebsiella, Pseudomonas*, *Staphylococcus, Enterobacter, Streptococcus, Serratia, Bacillus*, and *Proteus* (*Fakoorziba et al., 2010*; *Kassiri, Kasiri & Quaderi, 2014*; *Kassiri, Kassiri & Kazemi, 2014*; *Sharawi, 2023*). In the 1950s, one research study indicated the correlation between cockroach infestations and hepatitis A (*Kapelinskaya et al., 2011*; *Tarshis, 1962*). Intestinal protozoa and helminth parasites such as *Entamoeba coli* and *Entamoeba histolytica/dispar* cysts, as well as *Enterobius vermicularis*, *Trichuris trichiura*, *Taenia spp*, and *Ascaris lumbri coidesova* cysts were isolated in 2008 in both the bodies and guts of the *Blattella germanica*, *Periplaneta brunnea* and *Pycnoscelus surinamensis* cockroach species (*Kinfu & Erko, 2008*). Another study showed that the presence of protozoa *Blastocystis homnisis* was responsible for digestive symptoms in the *Periplaneta americana* cockroach species (*Zaman et al., 1993*). Other experimental studies have demonstrated the vectorial potential of cockroaches. Finally, cockroach infestations can cause psychological issues (*Porusia, Ratni & Dhesi, 2020*; *Roth & Willis, 1960*).

Many other medically relevant pathogenic agents have been isolated in cockroaches from their body surfaces and in their excrement, in infectious environments such as homes, hospitals, and industrial settings (*Hashemi-Aghdam & Oshaghi, 2015*; *Fakoorziba et al., 2010*; *Kassiri, Zarrin & Veys-Behbahani, 2018*). In 1964, cockroaches were linked for the first time to allergic reactions (*Bernton & Brown, 1964*; *Bell & Adiyodi, 1982*). Cockroach infestations may cause asthma, rhinitis, eczema and other allergic diseases, especially given that they are a source of inhalant allergens (*Jiang et al., 2008*; *Do, Zhao & Gao, 2016*; *Sohn & Kim, 2012*).

Termites represent the most troublesome pests for both plants and buildings, and are responsible for more than US $40 billion in economic losses every year (*Rust & Su, 2012*). People in the United States spend more than US $11 billion each year on preventing, treating and repairing termite damage (*Janowiecki et al., 2021*). However, although termites cause enormous economic losses, they also perform work as ecosystem engineers, influencing the distribution and aggregation of phosphorus in the soil and increasing water infiltration (*Hasnaoui et al., 2022*; *Lin et al., 2024*). Studies have shown that termites are highly rich in proteins, vitamins, and calories and their use in the medical field has been reported to treat various diseases such as asthma and bronchitis. Other investigations have found that water extract of termite might reduce HIV-1 viral activity (*Zhang et al., 2023*).

Lepidoptera (moths and butterflies)

The Lepidoptera order represents some of the most abundant, ubiquitous, and economically significant insects, with over 120 families and around 160,000 known species, representing one of the major orders of Holometabola (*Resh & Carde, 2009*). This order is not typically associated with significant damage to historical artefacts and buildings. It includes both butterflies, which are helpful insects (silkworms), and

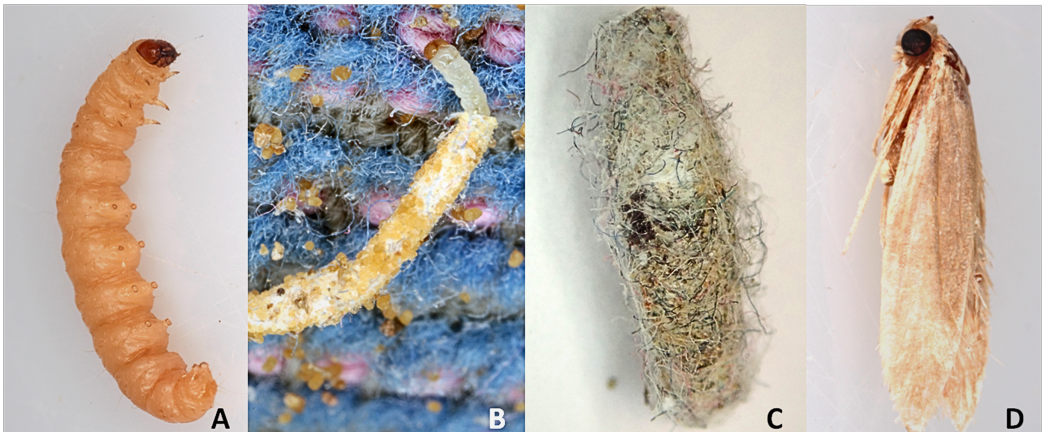

Figure 8 Lepidoptera. Common clothes moth (Lepidoptera) *Tineola bisselliella* (A) larvae profile view (B) larva dorsal view (C) cocoon (D) adult Tineola bisselliella.
Full-size DOI: 10.7717/peerj.18700/fig-8

moths which are harmful (crop pests) (*Triant, Cinel & Kawahara, 2018*; *Gandotra et al., 2016*). Few species within this order cause problems or pose a threat to cultural artefacts, historical buildings, and valuable collections. Several mummies and human remains have been found to contain moths and other arthropods (*Panagiotakopulu & Buckland, 2012*).

Tineola bisselliella, a webbing cloth moth, and *Tinea pellionella*, a case-bearing clothes moth (Order Lepidoptera) are the most significant pests and have a cosmopolitan distribution (Fig. 8). Of secondary importance are the pale-backed cloth moth known as *Monopis crocicapitella*, the brown house moth, *Hofmannophila pseudospretella*, the white-shouldered house moth, *Endrosis sarcitrella*, and the Indian meal moth, *Plodia interpunctella* (*Pinniger & Lauder, 2018*; *Querner et al., 2018*).

The webbing cloth moth is responsible for significant economic losses around the world. Their larvae feed on wool, feathers, hair, and fur, causing damage to homes, clothes, and cultural items (*Kruger-Carstensen & Plarre, 2012*). Research indicates that they may originate from central and southern Africa. They represent the most significant and prevalent cloth moth on the planet and belong to the family Tineidae within the superfamily Tineoidea (*Davis & Robinson Gaden, 1998*). Classified as a museum insect pest and found all over the world (*Querner, 2016*), harm caused by this species was reported in a biological collection for the first time in Mexico (*May-Vega et al., 2018*).

Tinea pellionella, also known as the case-bearing cloth moth, has been present in Britain for over a thousand years. Birds' nests and animal carcasses represent their natural habitat (*Pinniger & Lauder, 2018*).

Biology of lepidoptera

Adult females lay their eggs separately or in groups, attached to the surface with an adhesive (*Trematerra & Fontana, 1996*). At around 10 days, the eggs hatch and larvae emerge. There are usually five or six larval instars which develop into the pupae stage. The larval stage can last for 30 months, moderated by the environment conditions (food,

temperature, humidity) (*Cox & Pinniger, 2007*). The larvae stop feeding and usually spin a tough, spindle-shaped, silken cocoon in which they pupate. Adults lack functional mouthparts, their purpose being to reproduce and lay eggs (*Medha et al., 2021*).

Damage to and impact on human health

Moths are responsible for serious and irreversible damage to fabric, furnishings, textiles, artworks, and other manufactured items involving materials of both animal and plant origin. One study has shown that damage caused by cloth moths is more serious than that caused by beetles (*Bry, 1991*; *Schwabe et al., 2021*). The damage can affect stored products, domestic items, and museum artefacts (*Querner, 2016*). Moth species have been reported to infest stored animal products, and losses of up to 50% of product yields have been reported (*Rajendran & Hajira Parveen, 2005*).

Many museum pests were reported to have destroyed artefacts made of wood, fabric, fur, feathers, felt, and other animal or plant materials at three major museums in Vienna. The pests included the *Tineola bisselliella* moth, which has been classed as a species of museum pest (*Querner, 2009*). According to the literature, the larvae of the brown house moth *Hofmannophila pseudospretella* occasionally eat the glue from moist books, which causes the condition of the books to deteriorate (*Pinniger & Lauder, 2018*).

Unlike some other insects, species in the Lepidoptera order do not generally have a direct impact on human health. However, it has previously been shown that insects such as moths and butterflies can exacerbate the symptoms of bronchial asthma. This has been proven in asthmatic Japanese patients, where immunology exams showed the presence of antibodies against midges and moths (*Komase et al., 1997*). Other cases have reported allergic skin and respiratory reactions caused by bee moths (*Asero et al., 2008*).

Zygentoma (the common silverfish and the long-tailed silverfish)

Zygentoma, commonly known as bristletails, form a primitive order of wingless insects. They have been documented for over 400 million years (*Smith, Mitchell & Mesaglio, 2022*), and are comprised of five families. Among these, only members of the Lepismatidae family are commonly found indoors. The main species in this family are the long-tailed silverfish, the common silverfish, and the firebrat (*Chen et al., 2019*). The common silverfish presents as a significant pest, particularly for museums, libraries, and other buildings, as they have a tendency to feed on various materials such as paper, cotton, starch, and cereals (*Wang et al., 2006*). These urban pests are commonly found in close proximity to humans and tend to reside in areas such as bathrooms, basements, and attics (*Mallis, 1990*). Over the ten last years, the long-tailed silverfish or giant silverfish *Ctenolepisma longicaudatum* has begun to represent a threat to libraries, archives, and museums in Europe (*Querner & Sterflinger, 2021*), due to its potential to damage valuable and irreplaceable items such as graphic collections, photographs, paper-based modern art, historic documents, and books (*Rukke et al., 2023*). This species is particularly troublesome in modern buildings, where it can reach high densities and spread between rooms and apartments (*Aak et al., 2020*). *Lepisma saccharina* is a species of silverfish that is commonly found in human habitats (*Boquete et al., 2008*). According to a survey to assess the prevalence of silverfish in 65

Spanish homes, 42% of the structures inspected were found to be infested with this species, along with at least one species from the *Ctenolepisma* genus (*Molero-Baltanás, Gaju-Ricart & de Roca, 1997*). The majority of the time, four species of silverfish are found within buildings, namely *Lepisma quadriseriata (Ctenolepisma lineatum), Lepisma. saccharina, Thermobia domestica*, and *Ctenolepisma longicaudatum* (*Aak, Hage & Rukke, 2020*; *Querner, 2015*).

Damage to and impact on human health

Silverfish are seen by homeowners as a nuisance and may have an indirect impact on human life, in both the economic and medical fields (*Barletta, Felice & Pini, 2007*; *Savoldelli et al., 2021*), Researchers conducted a study of insect abundance using traps placed in various museums during the COVID-19 pandemic in Vienna. The results showed an increase in the number of common silverfish (*Lepisma saccharina*), as well as the long-tailed silverfish (*Ctenolepisma longicaudatum* and *Ctenolepisma calva*) in some museums. Although other insects were also found, their numbers did not increase significantly over the same period (*Brimblecombe, Pachler & Querner, 2021*). Research has shown that household dust harbours substantial levels of antigens originating from silverfish. In the early 21st century, one study suggested that silverfish could be a significant source of indoor inhalant allergens. Scientists subsequently isolated a specific component, rLet s 1, from silverfish and demonstrated its ability to trigger allergic reactions in patients (*Barletta et al., 2002*). These hypersensitivity reactions occurred through various routes of exposure, including inhalation, ingestion, and parenteral administration (*Barletta et al., 2005*). Based on these results, further research demonstrated IgE sensitisation to *Lepisma saccharina* (common silverfish) in children with respiratory allergies. The study revealed a high frequency of IgE binding to specific proteins in the silverfish extract.

Psocoptera

The name "Psocoptera" is derived from the Greek terms "psochein", which means "crushing" and "pteron" which means "wing". They are terrestrial insects with small, soft bodies, less than 6 mm in length (*Heo et al., 2010*).

According to fossil records, they originally emerged in the Permian era, hundreds of millions of years ago (*O'Toole, 2002*), and live mainly on vegetation and on edaphic material. All stages feed on microflora, algae, and fungi (*Lienhard & Mifsud, 2015*). Flakes of skin from humans and their pets are consumed by some psocids (*Eldridge & Edman, 2012*). They can be found in mammalian and bird nests, particularly some species of the Proquillidae family (*Heo et al., 2010*), which live in bird nests and feed on dead skin cells without harming the bird. Some species eat the eggs of dead insects (scavengers), while others feed on starchy items such as books, bindings, and wallpaper paste (*Eldridge & Edman, 2012*).

Psocids (Psocoptera) are pests that have a negative impact on grains and other amylaceous products. They can grow in a wide range of cereal products, and multiply quickly, especially when they are subjected to a humid conditions which encourages the

Figure 9 **Psocoptera.** Psocoptera species *Liposcelis sp*. adults (A) and *Liposcelis* in natural habitat (B).
Full-size DOI: 10.7717/peerj.18700/fig-9

development of fungus, their primary food source (*Athanassiou et al., 2012*; *Nayak et al., 2014*). They infest domestic homes, stores of raw materials, manufacturing plants, and historical documents in museums (*Liu et al., 2014*). Their common names of "bark lice" and "booklice" are related to their tendency to infest books. The World Catalogue of Insects lists over a thousand known species (*Anonby, 2019*) and 35 families around the world. Very few studies have been conducted in European countries such as Bulgaria (*Georgiev, 2020*), Belarus (*Ostrovsky & Georgiev, 2020*), and Malta (*Lienhard & Mifsud, 2015*).

Most species associated with human habitats belong to the suborders Trogiomorpha and Troctomorpha. Species such as *Lepinotus reticulatus, Liposcelis bostrychophila, Cerobasis annulata*, and *Cerobasis guestfalica* are abundant, especially when conditions are favourable (*Lienhard & Mifsud, 2015*; *Mockford, 1993*), such as in humid rooms following water damage, basements, wet walls, and room partitions, where they can find optimal conditions for development (Fig. 9) (*Baz & Monserrat, 1999*). Libraries, bookshops, and paper stores are other common habitats for these insects (*Veraldi, Brena & Süss, 2019*).

Due to transport and trade in commercial goods, psocids are spread around the world, and the geographical origin of several domestic species is unknown. *Dorypteryx domestica*, a species of *Psocidae*, has been described in human habits in Africa, North America and at least 16 European countries (*Rueckert & Devetak, 2017*). Since the 20th century, *Psocoptera* and several species of the family Liposcelididae have been considered as a threat to human life and stored products, as they cause severe germ damage and weight loss in stored grain (*Athanassiou et al., 2014*). Nearly a hundred species of psocids have been documented as infesting stored products, with four of them, *Liposcelis bostrychophila, L. decolor, L. entomophila*, and *L. paeta*, causing substantial economic losses worldwide (*Nayak et al., 2014*).

Biology of Psocoptera

Psocids have a tropism to wet areas. A temperature of 22 °C to 33 °C, with 70% to 80% relative humidity, is ideal for their growth and multiplication. While a low temperature of 2 °C is undesirable for adult survival, the eggs may survive and hatch as soon as

temperature and humidity conditions become favourable (*Pinniger & Lauder, 2018*; *Rees & Rangsi, 2004*).

Psocids exhibit a variety of reproductive patterns, with females depositing between 50 and 100 eggs during their lifetime. However, some psocids, such as Archipsocopsis and Phallocaecilius, are viviparous. Eggs can be deposited alone or in clusters and the entire embryonic development takes place within the mother's ovary (*Cano & Cano Ortiz, 2012*; *Gavrilov-Zimin, 2021*).

Typically, nymphal development covers six nymphal instars before reaching adulthood. Egg hatching takes between 1 and 4 weeks, and a nymph emerges in the first stage of development. The psocids have no pupal stage and are the number of stages is occasionally reduced to five, four, or even three. Under optimum conditions, the pest's life cycle is completed in 21 days (*Mockford, 1993*).

Parthenogenesis is known to occur in about 15 families of the three Psocoptera suborders (*Mockford, 1971*). The literature reveals that psocid infestations increase in warmer climates, a fact demonstrated by the installation of 30,000 insect traps in English heritage properties (*Brimblecombe & Brimblecombe, 2015*).

Damage to and impact on human health: allergies and Rickettsia

The economic impact of psocids on stored products has been estimated as weight loss of between 5% and 10% (*Nayak et al., 2014*). Psocids, like other insects, have been linked to cases of dust allergies in humans (*Turner et al., 1996*). There is no evidence in the scientific literature of their role as pathogen vectors. However, many studies have demonstrated the presence of *Rickettsia* and suggest that they play a role in the early development of the oocyte (*Škaljac, 2012*; *Clemmons & Taylor, 2016*). Others have suggested that *Rickettsia* is an obligate symbiont of *L. bostrychophila* (*Yang et al., 2015*, *2013*; *Li et al., 2011*).

Their existence in household dust and museums exacerbates symptoms of dust allergies (conjunctivitis, rhinitis, and dermatitis) (*Patil, Niphadkar & Bapat, 2001*; *Ishibashi et al., 2017*; *Gautam, Opit & Shakya, 2016*; *Gautam, Opit & Giles, 2010*). This was demonstrated in the description of a patient who began working at an antique bookstore (*Veraldi, Brena & Süss, 2019*) and developed an allergy.

Approaches used for pest identification

The identification of insect pests belonging to the orders Coleoptera (beetles), Blattodea (cockroaches and termites), Psocoptera (booklice), and Lepidoptera (moths and butterflies) is a key step towards protecting historic buildings and artefacts as well as towards successful pest management (*Pinniger & Lauder, 2018*; *Museumpests.net, 2023*). Using various types of dichotomous keys, such as those published by Gorham in 1991 for cockroaches, Coleoptera, and mites (*Hagstrum, 2017*), and those developed by *Bordereau et al. (2003)*, *Bouillon & Mathot (1965)* for termites, we can ensure the accurate and precise identification of these species. The morphological identification approach may differ depending on the order. Identification of Blattodea species (cockroaches and termites) uses a combination of criteria including the morphology of different parts of the insect such as

the shape, the size of the head, pronotum, abdominal segment, legs, wings, and, in some cases, the mandibule (*Krishna et al., 2013*; *Bouillon & Mathot, 1965*; *Roth & Willis, 1960*). Dissection of the genitalia and intestinal segments can provide information about species identification (*Hellemans et al., 2021*; *Roth, 2003*). Identification of Lepidoptera species in adults can be based on hindwing veins M2 and M3, antennal flagellum, male maxillary palpus, and the male abdominal segment, sometimes requiring the dissolution of soft tissues and dissection of the abdomen so that the structure of the genitalia can be examined (*Chen et al., 2020*; *Roe et al., 2015*). Identification of Coleoptera (beetles) remains challenging due to the diverse range of their life stages (*Malewski, Łoś & Sołtyszewski, 2019*). The identification of Coleoptera often involves the use of morphometric and genitalia criteria. Identification of larvae includes the number of abdominal segments, overall body coloration, body shape, and the structure of the head capsule (*Notton, 2018*; *Díaz-Aranda et al., 2018*). Psocoptera identification involves morphometric measurements including head length, post clypeus distance, head width, the distance between the sides of the head, and the quotient of head length and head width (*Li et al., 2011*), and is commonly conducted using microscopic examination of certain internal organs (*Richoux, 1999*).

Molecular biology has opened the way for various alternative approaches to arthropod identification, based on DNA sequences such as DNA barcoding, which helps with the determination and classification of different species (*Hebert et al., 2003*), PCR amplification, and DNA sequencing using various markers such as *COI*, *COII*, *16s rRNA*, *ITS 2* and *cytochrome b* (*Singh et al., 2022*).

The proteomic tool, MALDI-TOF MS, has been applied successfully to arthropod species identification of haematophagous arthropods such as fleas, lice, mosquitoes, ticks, bed bugs, and phlebotomine sand flies (*Sevestre et al., 2021*). The use of this tool has recently proven successful in identifying termite species collected from diverse origins (*Hasnaoui et al., 2022*).

CONCLUSION

Many of these insect pests play essential roles in nature. They act as "cleaners" by feeding on corpses, dead wood, and debris, while also serving as crucial links in the food chain for other insects and animals, such as termites. However, when they invade our homes and target our belongings and food, they become unwelcome pests. Human activities, particularly international trade, have led to the widespread distribution of these insects, and this trend is unlikely to change. Wherever humans go, these insects can be found.

Though these insects do not transmit diseases, they affect human health through allergies and direct or indirect dermatological reactions, including skin irritations caused by their bristles and parasitic infestations such as *Pyemotes* and *Sclerodermus*. Additionally, their effect on stored food can lead to potential food shortages, raising concerns around human nutrition.

To strike a balance in the ecosystem and to minimise negative impacts on human health and well-being, it is crucial to implement effective pest management strategies. Further research is needed to better understand their biology, behaviour, and interactions. These

insights could help to develop sustainable solutions to our coexistence with these insects while ensuring our environment and our resources are protected.

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Author Contributions

- Bouthaina Hasnaoui conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Fabien Fohrer conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Philippe Parola analyzed the data, authored or reviewed drafts of the article, and approved the final draft.
- Jean-Michel Berenger conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

This is a literature review.

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