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Integrative Roles of Carabidae: Ecology, Bioindicator, Agricultural Value, and Biomedical Potential

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Abstract: Ground beetles (Coleoptera: Carabidae) are among the most ecologically diverse and functionally important insect families in terrestrial ecosystems. This review consolidates current knowledge on their morphology, feeding strategies, ecological adaptability, and distribution patterns, emphasizing their roles as bioindicators and natural enemies in agricultural systems. Carabidae are highly sensitive to habitat structure, environmental degradation, and pollution, making them valuable for conservation planning and ecological monitoring. Their predatory behavior significantly helps control agricultural pests, while their capacity to bioaccumulate heavy metals offers a reliable basis for environmental risk assessment. Additionally, the family's unique chemical defense systems, including reactive quinones, hydroquinone, hydrogen peroxide, and volatile irritants, exhibit complex biochemical pathways that are increasingly relevant to biomedical research, such as antimicrobial activity, antitumor mechanisms, controlled drug release, and microreactor-inspired technologies. By combining taxonomic, ecological, agricultural, and biochemical perspectives, this study highlights the diverse contributions of Carabidae to biodiversity assessment, sustainable agriculture, and biomimetic innovation.

Keywords: Agriculture, Biodiversity indicators, Biological control, Biomedical research, Environmental conservation, Insect pests, Predator.

Research Paper

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1. INTRODUCTION

The order Coleoptera is home to insects popularly known as beetles. They are considered important agents of entomofauna richness as they comprise approximately 40% of the species within the Insecta class and 30% of the Animalia kingdom. They have around 360,000 described species and can be found in various habitats and ecological niches (Ball and Shpeley, 2000; Martinez, 2005; Bouchard *et al*., 2017).

The Carabidae family belongs to the order Coleoptera and suborder Adephaga, formed by beetles with a cursorial and predatory habit, generally found in sandy terrain, under rocks and litter; however, some groups are found in trees and shrubs. The occurrence of carabids can determine important characteristics of planting, in addition to contributing to the biological control of insect pests. The Carabidae are one of the most numerous families, with almost 40 thousand described species. They are distributed throughout the world with a higher specific richness in tropical regions (Ball and Shpeley, 2000; Bouchard *et al.,* 2017; Cerón-Gómez and Márquez, 2023).

Carabid beetles inhabit an exceptionally wide range of environments, occurring in both aquatic margins and dry terrestrial ecosystems. Their distribution spans broad thermal limits, with many species tolerating temperatures from 10°C to nearly 50°C. Because most species are active predators, particularly of caterpillars presence is ecologically desirable. Both larvae and adults are vigorous hunters and are typically found beneath leaf litter, rocks, or other ground cover while searching for prey (Figure 1) (Bouchard *et al.,* 2017; Cerón-Gómez and Márquez, 2023).

Figure 1: Adults of the native carabid beetle *Lebia grandis* Hentz, 1830, are voracious predators of *Leptinotarsa decemlineata* (Say, 1824) (Lepidoptera) Colorado potato beetle eggs and larvae
Source: ARS photo d1518-1 by Peggy Greg

2.0. METHODS

This study consists of a structured literature review that synthesizes biological, ecological, and functional information on *Carabidae* as bioindicators and biological control agents. Scientific articles were searched in the CAPES Periodicals Portal, Web of Science, Scopus, SciELO, and Google Scholar between January and June 2024, using combinations of the terms Carabidae, bioindicators, biodiversity, biological control, and agroecosystems. Publications were selected based on the following criteria: (a) peer-reviewed studies; (b) relevance to morphology, ecology, conservation, or agricultural importance of Carabidae; (c) availability of full text; and (d) studies published in English, Spanish, or Portuguese.

Duplicate papers and studies lacking ecological applicability were excluded. Data extracted from the selected literature were organized into thematic categories, morphology, bioecology, environmental indicators, agricultural relevance, and taxonomy, to allow comparison across studies. The synthesis was narrative, focusing on recurring ecological patterns and functional traits related to environmental monitoring and pest control. No experimental procedures were conducted, and all sources were properly cited following ethical research standards.

3.0. RESULTS AND DISCUSSION

3.1. Morphology

Carabid beetles exhibit substantial diversity in size, coloration, and body shape. Despite this variation, they share diagnostic traits that facilitate their identification. The head is narrower than the pronotum, which is disc-shaped and hosts the first pair of legs. The elytra, modified forewings, protect the membranous hindwings and abdomen. Eyes are typically prominent, and the antennae, inserted between the eyes and mandibles, contain 11 antennomeres. The mandibles are large, sharp, and adapted for predation (Figure 2) (Ball and Shpeley, 2000; Lawrence, 2013; Bouchard *et al.,* 2017; Cerón-Gómez and Márquez, 2023).

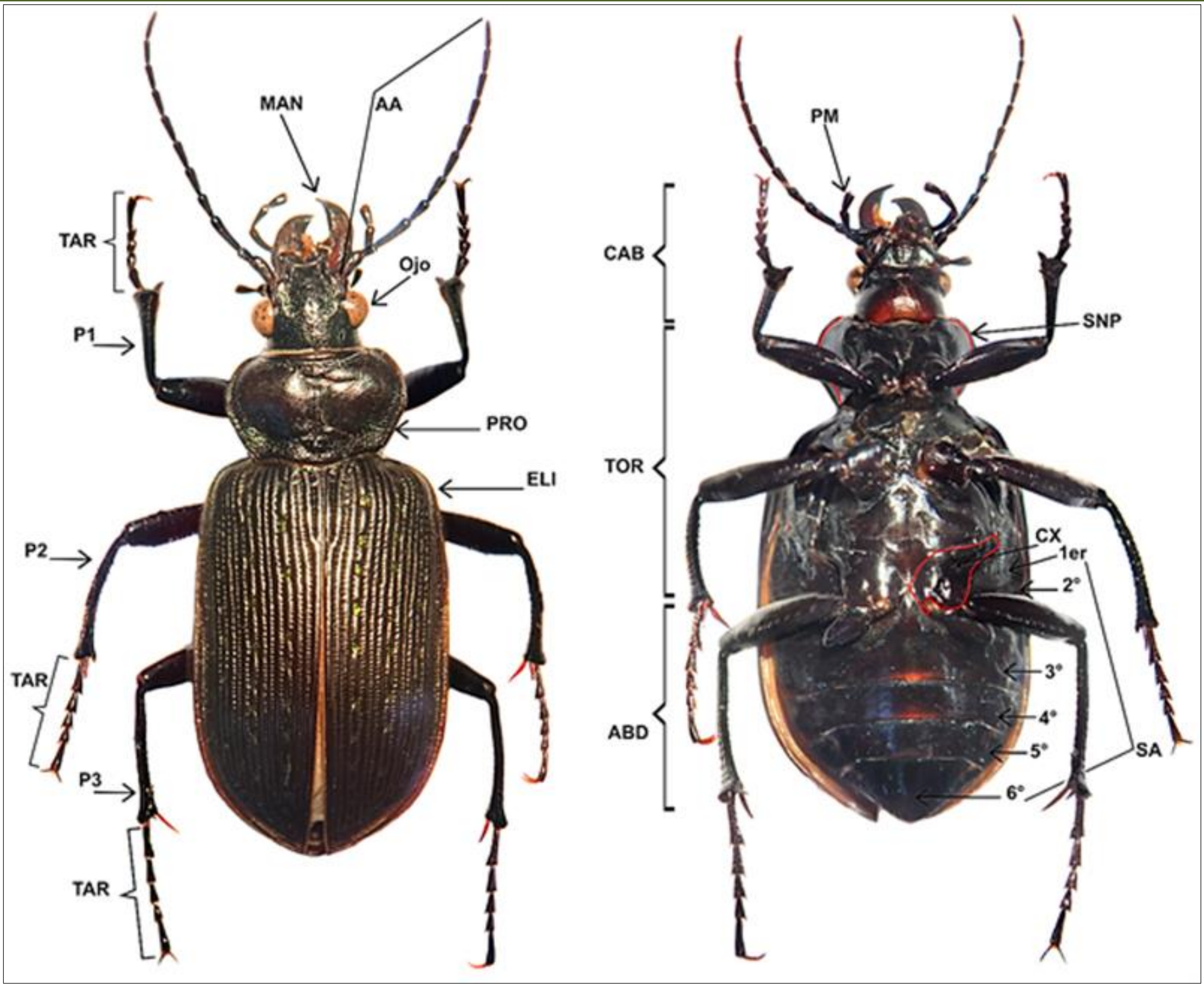


Figure 2: *Calosoma alternans* (Fabricius 1792), showing the most relevant characteristics of Carabidae. AA: antennal joints, ABD: abdomen, CAB: head, CX: coxa (retouched in red), ELI: elytra, MAN: mandible, PM: maxillary palps, PRO: pronotum, P1: anterior legs, P2: legs stockings, P3: hind legs, SA: abdominal segments, SNP: notopleural suture (retouched in red), TAR: tarsomeres, TOR: thorax

Sources: Doi: http://doi.org/10.22201/cuaieed.16076079e.2023.24.4.11 and Credit: Asian J

In the ventral view, a clearly defined printed line called "notopleural suture" can be seen, as it runs parallel to the external margin of the pronotum. The elytra completely cover the abdomen. Many species are brachypterous, which means that the second pair of wings, which are membranous, is reduced, and this prevents them from flying. The three pairs of legs are long and thin; their last joint is called the tarsus and is divided into five parts, which are called tarsomeres (Ball and Shpeley, 2000; Lawrence, 2013; Bouchard *et al.*, 2017).

Ventrally, the pronotum displays the notopleural suture, running parallel to its lateral edge. Many species are brachypterous, possessing reduced hindwings, which prevent flight. The three pairs of legs are elongated, and the tarsi consist of five tarsomeres. The first abdominal segment is divided by the hind coxae, and the trochanter is notably elongated compared to other beetle families. While many carabids exhibit dark coloration, iridescent and metallic forms are also common (Figure 3) (Magura and Lövei, 2020; Wagner *et al.,* 2021; Cerón-Gómez *et.al.,* 2022).

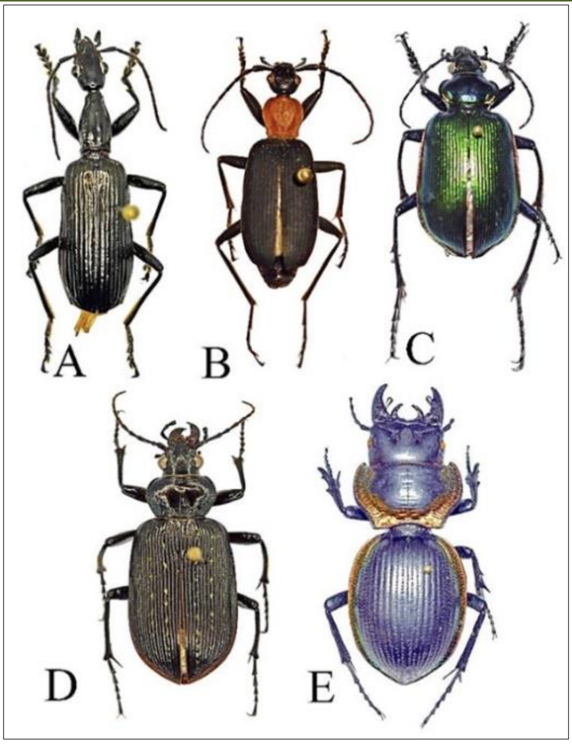


Figure 3: Adult specimens of the family Carabidae. A) *Agra* sp. Fabricius, 1801. B) *Galerita mexicana* (Chaudoir, 1872). C) *Calosoma aurocinctum* Chaudoir, 1850. D) *Calosoma alternans* (Fabricius 1792). E) *Mouhotia batesi*, Lewis 1879

Source: Credit: Own elaboration

3.2. Bioecology

As key predators within terrestrial ecosystems, carabid beetles regulate invertebrate biodiversity. Their diet consists primarily of other arthropods, though some species consume small vertebrates such as amphibians. Carabids occupy a broad spectrum of habitats, including caves, forests, wetlands, coastal environments, grasslands, and high-altitude ecosystems (Figure 4) (Ball & Shpeley, 2000; Erwin, 2008; Erwin, 2011; Erwin, 2014).

Figure 4: Ground beetles (Family Carabidae) Larva (e) 21mm long

Sources: Image Number: 5535795 and Photographer: Joseph Berger

They are typically found under rocks, leaf litter, bark, decomposing logs, and other detritus. Most species, including both larvae and adults, exhibit nocturnal habits. While predominantly predatory, some are omnivorous, detritivorous, or herbivorous. Their ecological relevance in agroecosystems arises from their role as natural enemies of insect pests (Figure 5) (Lövei and Sunderland, 1996; Ball and Shpeley, 2000; Hayashi and Sugiura, 2021).

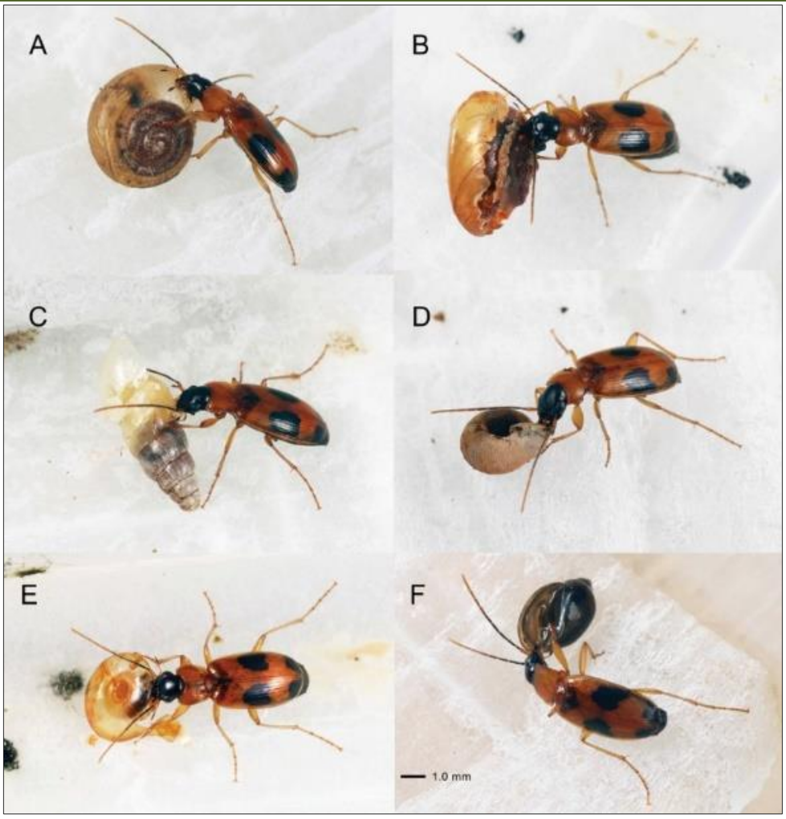


Figure 5: ***Badister pictus*** **Bates, 1873 (Carabidae), adults (A) adult biting the outer lip of** ***Zonitoides arboreus*** **(Say, 1816) (Mollusca) (B) adult feeding on the soft body after opening the shell of** ***Z. arboreus*** **(C) adult breaking the shell of** ***Opeas pyrgula*** **Schmacker & Boettger, 1891, (D) adult biting the outer lip of** ***Metalycaeus hirasei*** **(Pilsbry, 1900) ((E) adult feeding on the soft body of the broken shell of** ***Hippeutis cantori*** **(Benson, 1850) (F) adult biting the basal lip of the sinistral snail** ***Physa acuta*** **Draparnaud, 1805**
Source: https://zookeys.pensoft.net/article/62293/element/4/434//

Carabid beetles inhabit an exceptionally wide range of environments, occurring in both aquatic margins and dry terrestrial ecosystems. Their distribution spans broad thermal limits, with many species tolerating temperatures from 10°C to nearly 50°C. Because most species are active predators, particularly of caterpillars, their presence is ecologically desirable. Both larvae and adults are vigorous hunters and are typically found beneath leaf litter, rocks, or other ground cover while searching for prey (Gennard, 2007; Bouchard, 2011; Casari and Ide, 2012).

3.3. Life Cycle

1. **Egg:** Females lay their eggs in the soil or under leaf litter, ensuring there is enough food for the larvae when they hatch. The eggs are usually small and white or yellowish.
2. **Larva**: Once the eggs hatch, elongated, soft-bodied larvae emerge with sharp mandibles for feeding on insects and other invertebrates. At this stage, they are voracious.
3. **Pupa:** After several molts, the larva enters the pupal stage, in which its body undergoes a radical transformation. In this state, it remains immobile and protected within the soil while its tissues reorganize to develop into the adult beetle.
4. **Adult:** Finally, the beetle emerges as a fully developed adult. Depending on the species, it can live from a few months to several years, playing its role as a predator and ecological regulator in the ecosystem (Martinez, 2005; Bouchard *et al.,* 2017; Fenoglio *et al.,* 2019; Cerón-Gómez and Márquez, 2023).

The Carabidae generally peak during spring and summer, when adults mate and females oviposit. Reproduction involves internal fertilization followed by egg deposition, and hatching usually occurs within two to four weeks, depending on species and environmental conditions. Newly emerged larvae undergo several months of development and, like adults, are carnivorous. They contribute significantly to food-web dynamics by feeding on small insects and even conspecific larvae (Figure 6A) (Gennard, 2007; Bouchard *et al.,* 2017; Casari and Ide, 2012; Xueqin *et al.,* 2021).

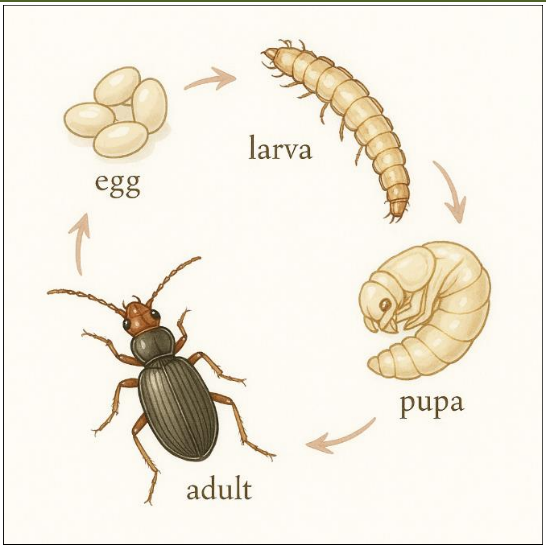
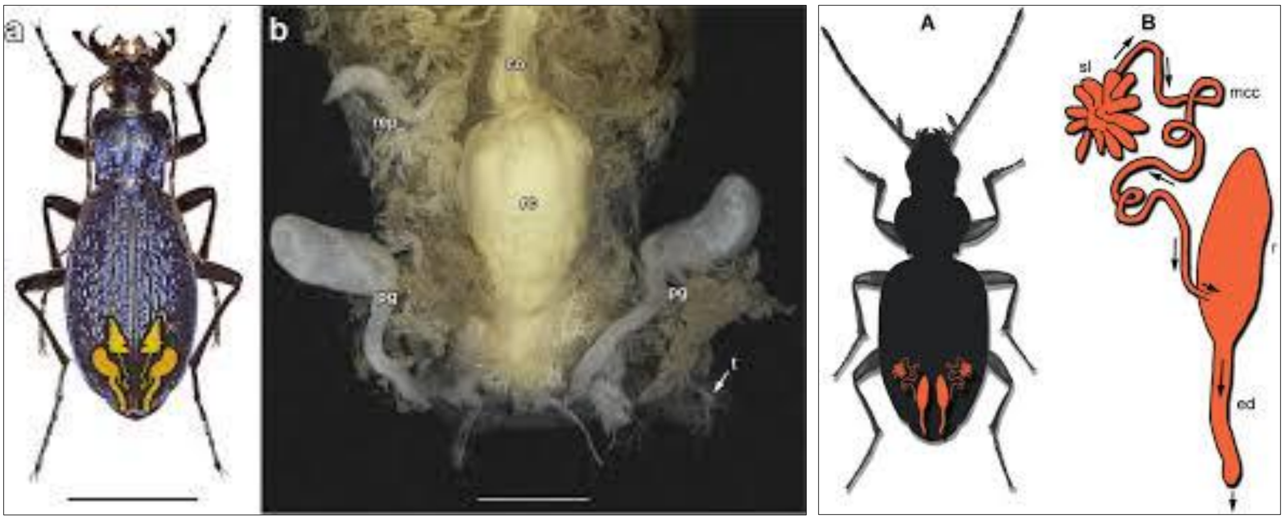


Figure 6: Ground beetles undergo a four-stage life cycle that includes egg, larva, pupa, and adult. Each stage progresses in sequence as the insect develops toward maturity. This simplified description highlights the essential transitions in Carabidae development

Despite their ecological importance, carabid beetles face numerous threats, including habitat loss, pollution, urban expansion, and the degradation of soil and water resources. These pressures compromise population stability and limit the ecological services provided by the group (Gennard, 2007; Bouchard, 2011; Casari and Ide, 2012; Xueqin *et al.,* 2021).

Among the most well-known members of Carabidae are the so-called "bombardier beetles," such as *Brachinus crepitans* (Linnaeus, 1758). These insects remain concealed under stones or roots and feed on soft-bodied arthropods. They are widely distributed worldwide except in Antarctica. (Gennard, 2007; Bouchard, 2011; Casari and Ide, 2012; Xueqin *et al.,* 2021).

Within the family, the subfamily Carabinae includes many robust ground beetles commonly referred to in Brazil as "carabídeos," "besouros-mentolados," or "besouros-cascudos." Many Carabidae species possess defensive glands capable of releasing corrosive, foul-smelling chemicals such as formic acid. When these secretions contact human skin, they may cause warming sensations, irritation, or transient discoloration, and in severe cases, superficial burns (Figure 6B) (Gennard, 2007; Bouchard, 2011; Casari and Ide, 2012; Xueqin *et al.,* 2021).



A B

Figures 7AB: Pygidial defensive gland of Carabidae showing (a) a general view of the glandular reservoir positioned in the posterior abdominal segments and (b) a detailed view of the excretory duct connected to the reservoir. The sac-like morphology and the gradual transition between the secretory region and duct reflect the functional organization of the chemical defense system

Source: Illustrations were enhanced from the original figures, preserving realistic anatomical features and coloration

3.4. Environmental Conservation and Biodiversity Indicators

Carabids have been used as indicator organisms in environmental pollution assessments, habitat classification for environmental conservation, soil characterization concerning nutrients, or biodiversity indicators. The Carabidae is a bioindicator group, as it has a large proportion of species with high ecological fidelity, is quite taxonomically and ecologically diverse, is easy to collect in large samples, and is functionally important in ecosystems (Figure 8) (Brown, 1991; Ball and Shpeley, 2000; Dar *et al.,* 2012; Quinteiro *et al.*, 2012; Xueqin *et al.,* 2021).

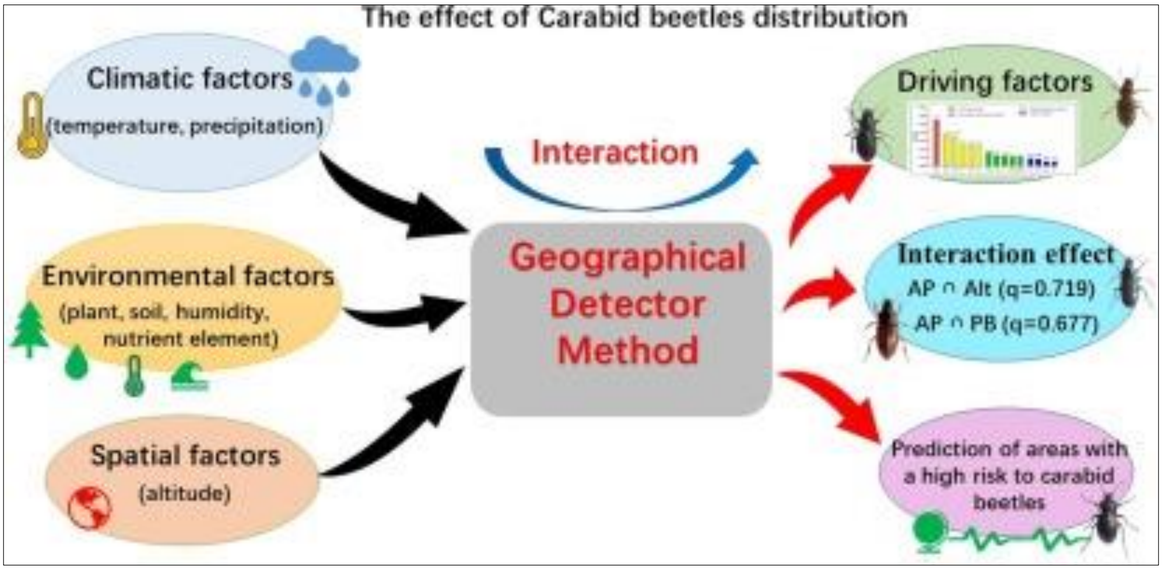


Figure 8: The geographic detector approach analyzes the driving forces of carabid beetle distribution and also offers a new method to understand the interactions between different drivers of other animal distributions more broadly. Carabid beetles are indicator species in the steppes of northwest China
Source: https://doi.org/10.1016/j.ecolind.2021.108393

They also form relatively well-known and identifiable taxonomic groups, in addition to being closely associated with other species and resources. Carabids have also been proposed as indicators in biodiversity survey programs because they exhibit significant morphological and behavioral variability and are sensitive to environmental changes (Ball and Shpeley, 2000; Jaskuła and Soszyńska-Maj, 2011; Makwela *et al.,* 2023).

Studies emphasizing predatory beetle communities in fragmented and reforestation areas are scarce. This survey aimed to identify species that can be used as bioindicators and obtain data on their population dynamics that can be correlated with the process of evaluating success in reforestation programs. The hypothesis was established that in forest fragments, a greater diversity of species from the Carabidae family and a lower abundance of individuals when compared to reforestation environments (Niemelä and Kotze, 2000; Siqueira *et al.*, 2015; Bouchard *et al.*, 2017; Jung and Lee, 2020).

3.5. Habitat and Entomology Forensic

Researchers commonly use ground beetles as efficient bioindicators because they respond sensitively to ecological variations caused by anthropogenic activities, such as overgrazing and soil or land pollution. Previous studies demonstrated a significant bioaccumulation of mercury and arsenic in *Carabus lefebvre* Dejean, 1826, confirming the species' suitability for assessing environmental contamination by these metals (Figures 9-11) (Blubaugh and Kaplan, 2016; Blubaugh *et al.*, 2016; Bouchard *et al.,* 2017).

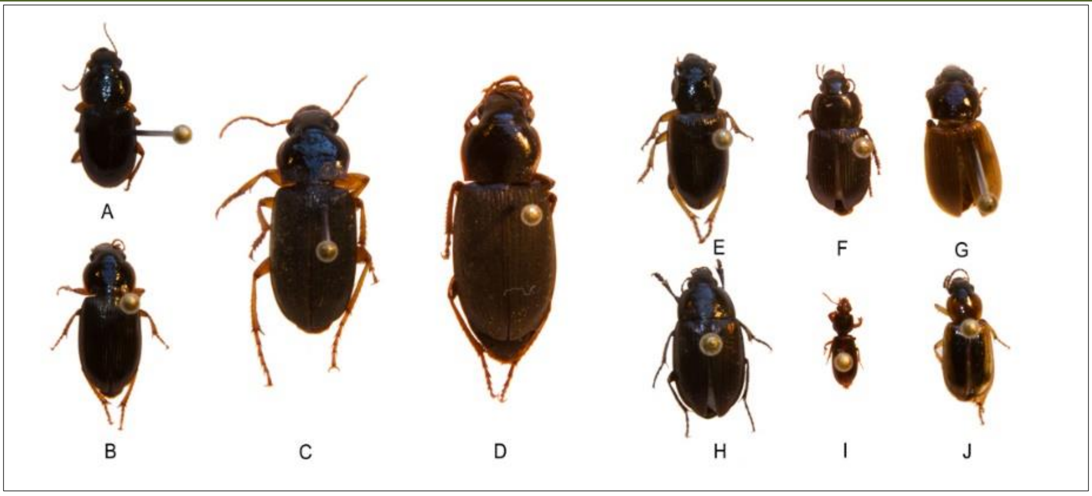


Figure 9: Granivores: (A-B) *Harpalus* spp.; C) *Harpalus rufipes* (DeGeer, 1774); D) *Harpalus* sp. (sp. refers to an unidentified species); E-G) *Anisodactylus* spp.; H) *Amara* sp.; I) *Clivinia* sp.; J) *Stenolophus* sp. These ground beetles are omnivores that primarily prey upon seeds

Source: Cooperative Extension: Maine wild blueberries beneficial insect series 2: Carabidae (ground beetles) on Maine farms

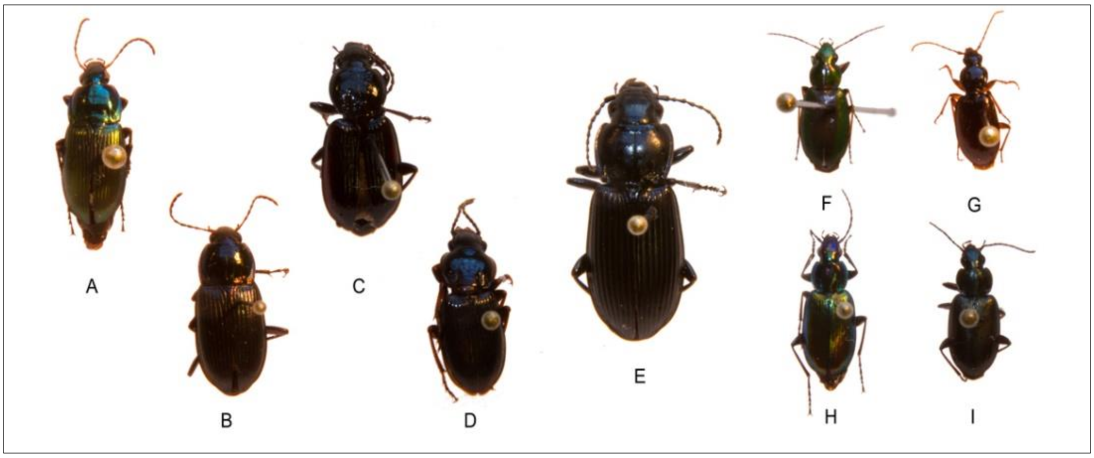


Figure 10: Omnivores: (A-B) *Poecilus lucublandus* (Say, 1823); C-E) *Pterostichus* spp.; F-I) *Agonum* spp. This group eats a variety of foods, including other insects, alive or dead, and seeds

Source: Cooperative Extension: Maine wild blueberries beneficial insect series 2: Carabidae (ground beetles) on Maine farms

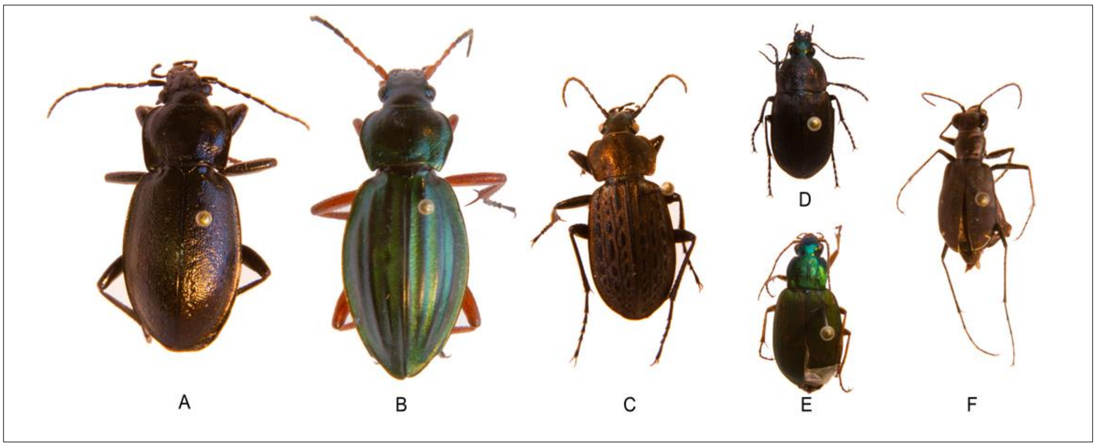


Figure 11: Generalist Carnivores: (A) *Carabus nemoralis* Müller, 1764; B) *Carabus maeander* Fischer von Waldheim, 1820; C) *C. meander*; D) *Chlaenius tomentosus* (Say, 1823); E) *Chlaenius sericeus* (Forster, 1771); F) *Cicindela* sp. These ground beetles consume a wide range of insect prey, including other ground beetles

Sources: Cooperative Extension: Maine wild blueberries beneficial insect series 2: Carabidae (ground beetles) on Maine farms

Ground beetles are commonly recognized as terrestrial predators, yet many species occupy a far wider ecological range than previously assumed. In tropical forests, for example, some carabids actively patrol the upper canopy, moving across branches several meters above the forest floor in search of prey. The specimen illustrated, captured at a height of 24 meters, demonstrates the remarkable vertical distribution of this group. Image: Brian Brown, Natural History Museum of Los Angeles County (Ball and Shpeley, 2000; Niemelä and Kotze, 2000; Gennard, 2007; Siqueira *et al.*, 2015).

Although carabids are frequently associated with leaf litter and the lower strata of vegetation, numerous studies reveal that different species partition forest habitats vertically. Some occur predominantly at ground level, where humidity and organic debris provide favorable microhabitats; others are commonly encountered in the mid-story, exploiting bark crevices, vines, and suspended litter; while a distinct subset is adapted to the canopy, where they hunt among epiphytes, flowers, and arthropod-rich foliage. This stratification suggests complex ecological specialization, allowing multiple species to coexist within the same forest while reducing competition and expanding the functional role of Carabidae across the entire vertical structure of vegetation (Casari and Ide, 2012; Bouchard *et al*., 2017; Jung and Lee, 2020).

3.6. Importance in the Agricultural

Agriculture relies heavily on ecological processes that regulate pest populations. Carabids play an essential role in this context due to their predation on a wide array of agricultural pests. Studies have investigated the diets of carabids in cultivated fields compared to natural habitats, providing insights into their value as biological control agents (Silva, 2018; Fenoglio *et al*., 2019; Cerón-Gómez *et al.,* 2022).

A major concern in agricultural landscapes is the use of pesticides and the potential contamination of soil and food. *Harpalus rufipes* has been employed as a bioindicator for detecting heavy metals accumulated as a consequence of agrochemical use. Significant concentrations of copper, magnesium, zinc, and cadmium have been detected in carabids sampled from wheat fields, demonstrating their ability to bioaccumulate pollutants and thus signal environmental risk (Figure 12) (Bouchard *et al.*, 2017; Silva, 2018; Naccarato *et al.*, 2020).

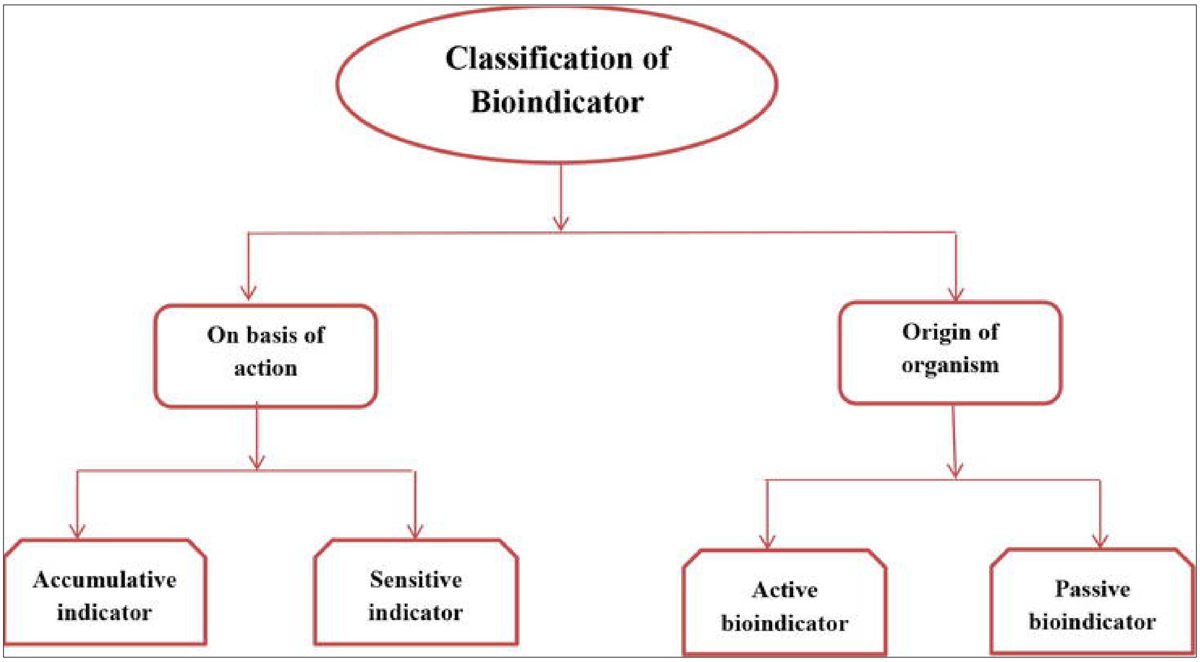


Figure 12: Schematic illustration of the classification of bioindicators. Classification of bioindicators based on mode of action and origin of the organism
Source: Doi:10.5772/intechopen.110212

One of the most debatable topics is the application of agrochemicals as pesticides, and the risks involved in their use due to the possible contamination of agricultural soil, crops, and damage to human health due to their consumption. An example of this is the measurement of concentrations of heavy metals or harmful substances, which was done in wheat fields in Italy as a consequence of the use of pesticides, using the species *Harpalus rufipes* (De Geer, 1774), a generalist predatory carabid (Figure 13) (Larochelle and Larivière, 2003; Fenoglio *et al*., 2019; Almayyahi, 2023; Márquez, 2023).

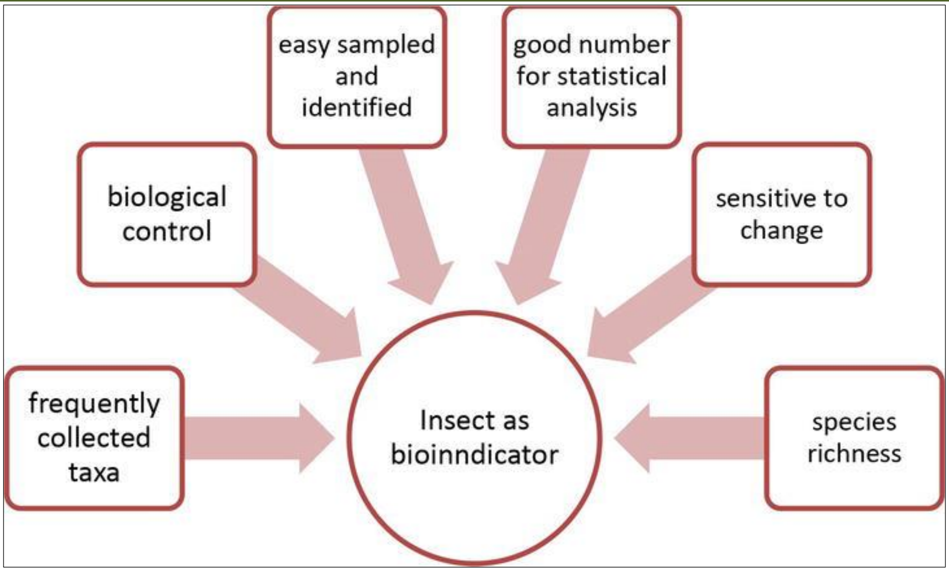


Figure 13: Researchers commonly use ground beetles as efficient bioindicators because they respond sensitively to ecological variations caused by anthropogenic activities, such as overgrazing and soil or land pollution. Previous studies demonstrated a significant bioaccumulation of mercury and arsenic in *Carabus lefebvre* Dejean, 1826, confirming the species' suitability for assessing environmental contamination by these metals
Source: Doi: 10.5772/intechopen.110212

Different concentration patterns were found in the collected individuals. Still, they determined that significant amounts of heavy metals were accumulated in the carabids, highlighting the regulatory capacity of this species to absorb these metals, with higher concentrations observed of copper, magnesium, zinc, and cadmium, they provide reference data showing the possible risks that agrochemicals pose to croplands (Figure 14) (Table 1) (Allen, 1979; Naccarato *et al*., 2020; Almayyahi, 2023).

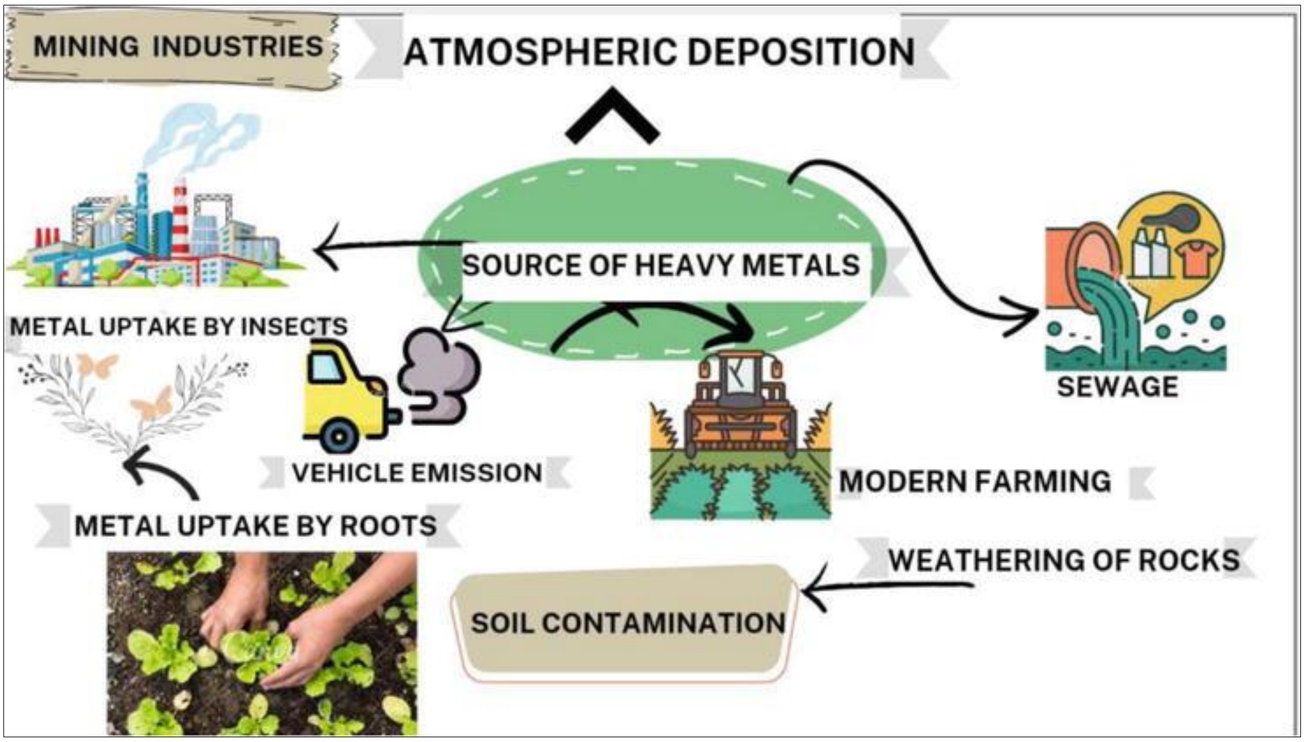


Figure 14: Various means of heavy metal pollution and their transfer to insects. Pollutant toxicity has impacted the biological processes as well as biotic interactions among living organisms, such as ecological structure, parasitism, and predator-prey relationships
Source: Doi: 10.5772/intechopen.110212

Table 1: Summarizes the key ecological and agricultural roles of Carabidae, highlighting their importance as predators, bioindicators, and regulators of ecosystem processes, particularly in pest control and environmental monitoring

Functional Category	Description	Representative Evidence
Bioindicators	Reflect habitat quality, fragmentation, pollution, and soil condition.	Used in monitoring forests, agroecosystems, and reforestation.
Predators of Agricultural Pests	Feed on insect eggs, larvae, slugs, and pest species.	Effective in controlling *Leptinotarsa decemlineata* (Say, 1824), Lepidoptera, and slugs.
Metal Accumulation	Accumulate heavy metals and contaminants.	Useful in pollution detection and risk assessment.
Ecosystem Regulators	Influence trophic networks and nutrient cycling.	Affect invertebrate communities across ecosystems.
Forensic Indicators	Appear during active decomposition stages.	Assist in post-mortem interval estimation.

The integration of the data presented in the figures and in Table 1 highlights the functional breadth of the Carabidae family. The morphological variations observed enable adaptations to multiple habitats, while the diversity of feeding habits reinforces their importance in regulating invertebrate populations and maintaining the ecological quality of ecosystems. Furthermore, their capacity to bioaccumulate heavy metals and respond to environmental disturbances makes these beetles essential tools for both environmental monitoring and sustainable agricultural management strategies (Bouchard *et al.*, 2017; Adhikari and Menalled, 2018).

3.7. Biomedical Potential of Chemical Compounds Produced by Carabidae

Their defensive system is remarkable: they eject a hot, noxious chemical spray from a specialized abdominal gland. Two separate reservoirs store hydroquinone and hydrogen peroxide, which react explosively when combined in the presence of catalytic enzymes. This reaction occurs within a reinforced combustion chamber whose cuticular lining protects the beetle from thermal and chemical damage. The discharge is delivered in rapid pulsations rather than a continuous jet, preventing self-injury while propelling the secretion, which may reach temperatures near 100°C, toward potential predators (Gennard, 2007; Bouchard, 2017; Casari and Ide, 2012).

This document summarizes the main chemical compounds released by Carabidae beetles, their biological significance, and their potential biomedical applications. All tables are formatted with visible borders for academic use. The chemical defenses produced by Carabidae illustrate an exceptional degree of biochemical specialization that has attracted significant scientific interest. These compounds, many of which are highly reactive or physiologically potent, provide both protection against predators and opportunities for biomedical exploration (Mukherjee and Patel, 2020; Vinuganesh *et al.*, 2022; Chukwudulue *et al.*, 2023; dos Santos *et al*., 2023; Craveiro, 2025).

Table 2 summarizes the major chemical substances identified in different Carabidae groups and highlights their known ecological functions alongside their potential applications in medical and pharmaceutical research.

Table 2: The text summarizes the diversity of defensive chemical compounds in Carabidae, highlighting their role in predator deterrence and ecological success, as well as their potential relevance for biomedical and pharmaceutical research

Compound	Expanded Biological Function	Expanded Biomedical Potential
Formic acid	Acts as a fast-acting corrosive secretion capable of disrupting the sensory systems of predators and providing immediate chemical defense.	Used in keratolytic treatments, antimicrobial formulations, and explored for controlled topical therapies.
Hydroquinone	Serves as a precursor in the bombardier beetle's exothermic reaction, enabling rapid catalytic oxidation and heat generation.	Applied in dermatology, antioxidant research, and studies on cytotoxicity for potential anticancer therapies.
Hydrogen peroxide	Functions as an oxidative component that, when catalyzed, contributes to thermal and kinetic energy in explosive defense.	Widely used as an antiseptic and studied for controlled oxidative medical treatments.
Benzoquinones	Provide long-lasting toxicity and irritation, protecting against predators across multiple species of Carabidae.	Display strong antimicrobial, antifungal, and antitumoral activity and serve as templates for drug development.
Volatile irritants	Mediate chemical communication and sensory disruption, augmenting defensive behavior.	Useful in research on polymer-based drug delivery and bioactive dispersal mechanisms.

Beyond their ecological relevance, the defensive compounds of Carabidae have inspired a wide range of biomedical innovations. The ability of these beetles to generate controlled chemical reactions, synthesize toxic quinones, or release antimicrobial acids offers valuable analogies for pharmacology, bioengineering, and clinical therapeutics. Table 3 outlines the primary areas of medical research in which Carabidae chemistry has contributed conceptual or structural insights.

Table 3: The text outlines how chemical systems evolved in Carabidae inspire biomedical and pharmaceutical applications, illustrating parallels with modern therapeutic, antimicrobial, and drug-delivery technologies and highlighting their potential to inform innovative medical and bioengineered solutions

Application Area	Expanded Description	Expanded Biomedical Insight
Antimicrobial therapy	Defensive acids and quinones display potent antimicrobial action against bacteria, fungi, and select parasites.	Potential scaffolds for next-generation antibiotics and topical antiseptics.
Cancer research	Quinone-based cytotoxicity induces apoptosis in abnormal or rapidly dividing cells.	Models for chemotherapeutic compounds and oxidative-stress-based cancer treatments.
Dermatological treatments	Hydroquinone regulates melanin synthesis and supports controlled skin-cell turnover.	Used to treat hyperpigmentation and investigated for broader dermatological applications.
Drug delivery engineering	Bombardier beetle micro-reactive chambers serve as natural analogs for controlled-release systems.	Inspires smart microcapsules and reaction-triggered drug delivery platforms.
Wound antisepsis	Oxidative compounds such as hydrogen peroxide provide effective disinfection.	Guides the formulation of rapid-acting wound treatment products.

Understanding the physical and biochemical mechanisms underlying Carabidae defense strategies provides an additional dimension of biomedical relevance. These mechanisms involve precise structural adaptations, controlled catalytic reactions, and efficient delivery systems that parallel emerging technologies in modern medicine. Table 4 presents examples of defensive processes in Carabidae and the biomedical concepts they have inspired.

Table 4: The text summarizes how defensive mechanisms evolved in Carabidae serve as models for biomedical technologies, highlighting their relevance to controlled-release systems, microreactors, and innovative therapeutic approaches

Biological Mechanism	Expanded Description	Biomedical Analogy
Explosive chemical chamber	A reinforced cuticular structure houses catalytic enzymes enabling explosive reactions without internal damage.	Model for microreactors, targeted drug activation, and heat-triggered therapeutics.
Pulsatile spray emission	Chemical discharge occurs in controlled pulses, preventing self-injury while maximizing defensive spread.	Basis for pulsatile dosing systems and dynamic-release pharmaceuticals.
Corrosive secretion release	Acids and quinones stored in abdominal glands can be rapidly mobilized for defense.	Template for topical formulations, antimicrobial compounds, and biochemical irritants used in medicine.

3.8. Classification

3.8.1. Subfamilies

Table 5 presents a selection of Carabidae species recorded in the regions studied, representing a wide range of morphological, ecological, and functional diversity within the family. These species include both broadly distributed genera and more specialized taxa, many of which play important roles in predation, seed regulation, soil processes, and environmental monitoring. The presence of genera such as *Brachinus* Weber, 1801; *Calleida* Sodovsky, 1837; *Lebia* Latreille, 1802; *Ozaena* Olivier, 1812, and *Scarites* Fabricius, 1775 illustrates the ecological breadth of Carabidae and highlights the importance of this group in Neotropical ecosystems. These records, supported by previous surveys, contribute to advancing the understanding of species richness and distribution patterns, while also reinforcing the relevance of Carabidae as bioindicators in biodiversity studies (Reichardt, 1977; Martinez, 2005; Zhang, 2013; Zaragoza-Caballero, 2016).

The Carabidae family, within the suborder Adephaga, is taxonomically diverse and comprises numerous subfamilies that reflect the evolutionary, ecological, and morphological breadth of this beetle group. The table 5 below summarizes the currently recognized subfamilies, along with their respective authors and year of description, following the classification proposed by Bouchard *et al.*, (2011).

Table 5: The text summarizes the taxonomic diversity of Carabidae subfamilies within Adephaga, emphasizing their evolutionary differentiation, ecological specialization, and global importance across diverse ecosystems

Subfamily	Author & Year
Apotominae	Leconte, 1853
Brachininae	Bonelli, 1810
Broscinae	Hope, 1838
Carabinae	Latreille, 1802
Cicindinae	Csiki, 1927
Cicindelinae	Latreille, 1802
Gehringiinae	Darlington, 1933
Elaphrinae	Latreille, 1802
Harpalinae	Bonelli, 1810
Hiletinae	Schiodte, 1848
Loricerinae	Bonelli, 1810
Melaeninae	Csiki, 1933
Migadopinae	Chaudoir, 1861
Nebriinae	Laporte, 1834
Nototylinae	Bänninger, 1927
Omophroninae	Bonelli, 1810
Patrobinae	Kirby, 1837
Paussinae	Latreille, 1806
Psydrinae	Leconte, 1853
Scaritinae	Bonelli, 1810
Siagoninae	Bonelli, 1813
Trechinae	Bonelli, 1810

This organizational framework not only highlights the historical development of Carabidae taxonomy but also underscores the extensive variation found within the group, ranging from highly specialized predatory lineages to species adapted to distinct ecological niches across different biogeographical regions. The presence of many of these subfamilies in Brazil further emphasizes the country's importance in the conservation and study of Carabidae diversity (Mukherjee and Patel, 2020; Vinuganesh *et al.*, 2022; dos Santos *et al*., 2023; Craveiro, 2025).

3.8.2. Species of Carabidae

Table 6 presents a selection of Carabidae species that illustrate the taxonomic and ecological diversity of the group across different habitats. These species represent various trophic strategies, morphological adaptations, and geographic distributions commonly documented in Neotropical environments.

Table 6: The text highlights the Carabidae genus and species selected as examples of the group's taxonomic and ecological diversity, emphasizing their varied adaptations, trophic roles, and importance for biodiversity assessment and ecological monitoring

Species	Authors / Year
Aephnidius	Esenbeck, 1818
Brachinus	Weber, 1801
Brachygnathus oxygonus	Perty, 1830
Callida amethystina	(Fabricius, 1787)
Callida metallica	Dejean, 1825
Colliuris	DeGeer, 1774
Coptia armed	Laporte, 1832
Dromius negrei	Mateu, 1973
Dyschirius	Bonelli, 1810
Lebia	Latreille, 1802
Leptotrachelus	Latreille, 1829
Lia nigropicta	(Chaudoir, 1871)
Megacephala fulgida	Klug, 1834
Odontocheila	Laporte, 1834
Oodes	Bonelli, 1810
Ozaena	Olivier, 1812
Pentagonica	Schmidt-Goebel, 1846

Species	Authors / Year
Scarites	Fabricius, 1775
Tichonilla festiva	(Chaudoir, 1869)
Trichognatus marginipennis	Latreille, 1825

Their occurrence in regional surveys contributes valuable information to biodiversity assessments, ecological monitoring, and future taxonomic studies (Bousquet, 2012).

3.8.3. Biomedical Potential of Chemical Compounds Produced by Carabidae

This document summarizes the main chemical compounds released by Carabidae beetles, their biological significance, and their potential biomedical applications. All tables are formatted with visible borders for academic use.

The chemical defenses produced by Carabidae illustrate an exceptional degree of biochemical specialization that has attracted significant scientific interest. These compounds, many of which are highly reactive or physiologically potent, provide both protection against predators and opportunities for biomedical exploration. Table 7 summarizes the major chemical substances identified in different Carabidae groups and highlights their known ecological functions alongside their potential applications in medical and pharmaceutical research (Mukherjee and Patel, 2020; Vinuganesh *et al.*, 2022; Chukwudulue *et al.*, 2023; dos Santos *et al*., 2023; Craveiro, 2025).

Table 7: The text summarizes the main defensive chemical compounds of Carabidae, emphasizing their ecological role and potential value for biomedical and pharmaceutical applications

Compound	Expanded Biological Function	Expanded Biomedical Potential
Formic acid	Acts as a fast-acting corrosive secretion capable of disrupting the sensory systems of predators and providing immediate chemical defense.	Used in keratolytic treatments, antimicrobial formulations, and explored for controlled topical therapies.
Hydroquinone	Serves as a precursor in the bombardier beetle's exothermic reaction, enabling rapid catalytic oxidation and heat generation.	Applied in dermatology, antioxidant research, and studies on cytotoxicity for potential anticancer therapies.
Hydrogen peroxide	Functions as an oxidative component that, when catalyzed, contributes to thermal and kinetic energy in explosive defense.	Widely used as an antiseptic and studied for controlled oxidative medical treatments.
Benzoquinones	Provide long-lasting toxicity and irritation, protecting against predators across multiple species of Carabidae.	Display strong antimicrobial, antifungal, and antitumoral activity and serve as templates for drug development.
Volatile irritants	Mediate chemical communication and sensory disruption, augmenting defensive behavior.	Useful in research on polymer-based drug delivery and bioactive dispersal mechanisms.

Beyond their ecological relevance, the defensive compounds of Carabidae have inspired a wide range of biomedical innovations. The ability of these beetles to generate controlled chemical reactions, synthesize toxic quinones, or release antimicrobial acids offers valuable analogies for pharmacology, bioengineering, and clinical therapeutics. Table 8 outlines the primary areas of medical research in which Carabidae chemistry has contributed conceptual or structural insights.

Table 8: The text outlines how chemical systems evolved in Carabidae inspire biomedical and pharmaceutical advances, highlighting their relevance to therapeutics, antimicrobials, and drug-delivery technologies

Application Area	Expanded Description	Expanded Biomedical Insight
Antimicrobial therapy	Defensive acids and quinones display potent antimicrobial action against bacteria, fungi, and select parasites.	Potential scaffolds for next-generation antibiotics and topical antiseptics.
Cancer research	Quinone-based cytotoxicity induces apoptosis in abnormal or rapidly dividing cells.	Models for chemotherapeutic compounds and oxidative-stress-based cancer treatments.
Dermatological treatments	Hydroquinone regulates melanin synthesis and supports controlled skin-cell turnover.	Used to treat hyperpigmentation and investigated for broader dermatological applications.
Drug delivery engineering	Bombardier beetle micro-reactive chambers serve as natural analogs for controlled-release systems.	Inspires smart microcapsules and reaction-triggered drug delivery platforms.
Wound antisepsis	Oxidative compounds such as hydrogen peroxide provide effective disinfection.	Guides formulation of rapid-acting wound treatment products.

Understanding the physical and biochemical mechanisms underlying Carabidae defense strategies provides an additional dimension of biomedical relevance. These mechanisms involve precise structural adaptations, controlled catalytic reactions, and efficient delivery systems that parallel emerging technologies in modern medicine. Table 9 presents examples of defensive processes in Carabidae and the biomedical concepts they have inspired (Mukherjee and Patel, 2020; Vinuganesh *et al.*, 2022; Chukwudulue *et al.*, 2023; dos Santos *et al*., 2023; Craveiro, 2025).

Table 9: The text highlights how Carabidae defensive adaptations provide models for biomedical technologies, particularly in controlled-release systems, microreactors, and protective biochemical processes

Biological Mechanism	Expanded Description	Biomedical Analogy
Explosive chemical chamber	A reinforced cuticular structure houses catalytic enzymes enabling explosive reactions without internal damage.	Model for microreactors, targeted drug activation, and heat-triggered therapeutics.
Pulsatile spray emission	Chemical discharge occurs in controlled pulses, preventing self-injury while maximizing defensive spread.	Basis for pulsatile dosing systems and dynamic-release pharmaceuticals.
Corrosive secretion release	Acids and quinones stored in abdominal glands can be rapidly mobilized for defense.	Template for topical formulations, antimicrobial compounds, and biochemical irritants used in medicine.

Figure 15 presents the main morphological features associated with chemical defense mechanisms in Carabidae, highlighting the structures responsible for the synthesis and release of bioactive substances. Building on this anatomical foundation, Figure 16 illustrates the sequential formation of defensive compounds, showing the chemical transformations that ultimately generate highly efficient volatile irritants.

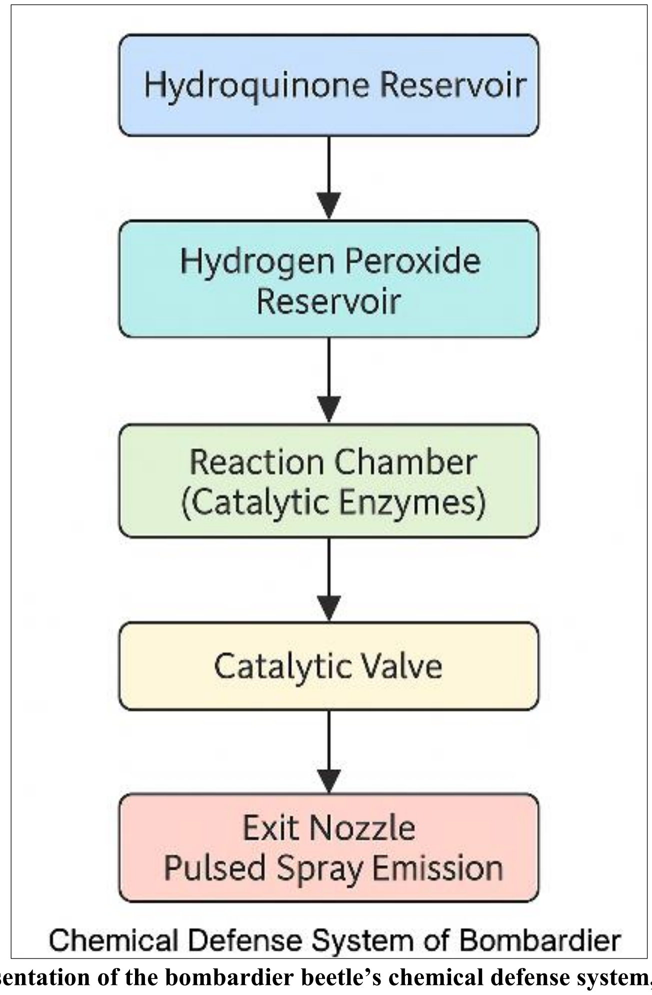


Figure 15: Schematic representation of the bombardier beetle's chemical defense system, showing the sequential flow from precursor reservoirs to the catalytic reaction chamber and final pulsed spray emission through the exit nozzle

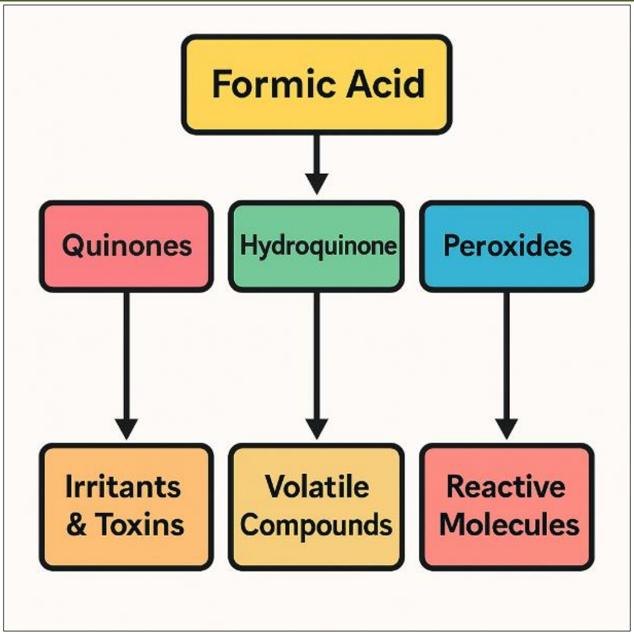


Figure 16: Formic acid acts as the central precursor leading to three major chemical pathways: the formation of quinones, hydroquinone, and peroxides. These intermediates subsequently generate distinct classes of bioactive products, including irritants and toxins, volatile compounds, and reactive molecules, each contributing to different defensive or signaling roles within arthropod chemistry

The mechanistic model outlined in Figure 17 demonstrates how controlled chemical reactions in Carabidae-inspired systems can generate heat, pressure, and pulsatile emission, providing a natural analogue for engineered drug-delivery technologies. Building on this concept, Figure 17 expands the discussion by illustrating how these biochemical processes integrate into broader biomedical applications, particularly those involving antimicrobial activity, cancer research, dermatological treatments, and microreactor-based release systems. Together, the two figures highlight the translational potential of Carabidae defensive chemistry and its relevance for the development of innovative therapeutic strategies (Rork and Renner, 2018; Mukherjee and Patel, 2020; Vinuganesh *et al.*, 2022; Chukwudulue *et al.*, 2023; dos Santos *et al*., 2023; Craveiro, 2025).

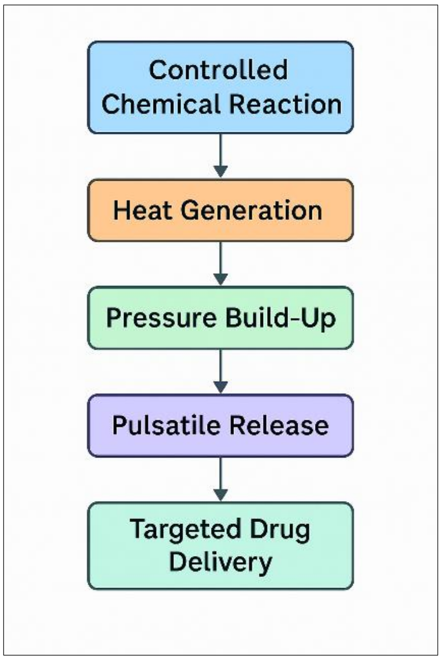


Figure 17: A controlled chemical reaction initiates heat generation, which subsequently leads to pressure build-up within the system. This increase in internal pressure triggers a pulsatile release mechanism, ultimately enabling targeted drug delivery with enhanced precision and efficiency

4. CONCLUSION

Carabid beetles occupy a central position in terrestrial ecosystems due to their trophic versatility, broad environmental tolerance, and ecological sensitivity. Their significance extends beyond predation and pest suppression, encompassing roles as reliable indicators of habitat quality, pollution levels, and ecological disturbance. Their ability to bioaccumulate heavy metals, respond predictably to environmental gradients, and reflect changes in landscape structure reinforces their value in conservation biology and agroecological management.

Furthermore, the highly specialized chemical defense mechanisms exhibited by many species, particularly the explosive reaction systems of bombardier beetles, reveal sophisticated biochemical adaptations with promising biomedical implications. These mechanisms inspire advances in antimicrobial therapy, dermatology, cancer research, and controlled drug-delivery systems. Collectively, the ecological, agricultural, and biochemical attributes of Carabidae demonstrate the interdisciplinary relevance of this group, underscoring its importance for biodiversity monitoring, sustainable farming practices, and biomimetic research aimed at developing innovative technological and therapeutic solutions.

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