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OPINION ARTICLE

The endless horizon of acarology: an assessment of the rhetoric of "science as the endless frontier"

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ASBTRACT: Scientific activity never constitutes a finished body of knowledge; on the contrary, each new answer constantly expands the field of knowledge by giving rise to deeper and more comprehensive questions. In this respect, science is a universe of research that expands as it progresses and whose boundaries can never be fully defined. In this article, the rhetoric of "science is an infinite frontier" is examined through the field of acarology. In the text, the microscopic nature of mites, their complex relationships within the ecosystem, and their biodiversity, are combined with concepts from the philosophy of science, and it is argued that acarology constitutes both a metaphorical and practical "infinite frontier" field in modern science. Thus, acarology is positioned as a good example of the unending horizon of science, revealing how epistemic openness and disciplinary plurality continuously redefine the boundaries of biological knowledges.

Keywords: Acari, organism-centered science, independent science, scientific pluralism, epistemic limits, disciplinary boundaries, knowledge expansion, uncertainty generation

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INTRODUCTION

Vannevar Bush (1890–1974), in response to a letter from U.S. President Franklin D. Roosevelt dated November 17, 1944 requesting a comprehensive roadmap for shaping national science and research policy to transfer the scientific knowledge accumulated through secret wartime work to peacetime, submitted a report to the presidency on July 5, 1945, entitled "*Science—the endless frontier*", in which he made visionary assessments regarding the vital importance of scientific research to the economic prosperity and security of the country. However, despite its title, the report does not directly or indirectly mention that science has an endless frontier. Bush's collection of articles, writings, and speeches from that period, titled "*Endless Horizons*" (Bush, 1946), also contains no direct textual definition or commentary on science having an endless horizon. However, it is generally accepted by the scientific community—though not absolutely, due to its sometimes regressive/degenerating nature—that science is a constantly expanding and deepening, dynamic process (Popper, 1962; Fuentes, 2025; Worrall, 2025). Bush's statement can be interpreted within a metaphorical (analogical) framework; indeed, Mayr (1997) made the following assessment from this perspective: *"...As Vannevar Bush has said so rightly, science indeed is an endless frontier.*"

Although Bush did not explicitly or implicitly state it, it is possible to speak of the existence of an "infinite boundary" in science. This is because science, with its own internal dynamics, constantly generates new areas of research, whether it progresses rapidly or slowly. The boundary of science is similar to the horizon: an image that recedes as you approach it, and then, just when you think you've reached it, it seems to expand and move further away again. Therefore, no matter how far science progresses, it presents a boundary that is not disappearing but constantly shifting. With this characteristic of having boundaries that cannot be defined with precise lines and that expand as it progresses, science can also be described as "the beginning of infinity" (Deutsch, 2011).

While this concept can easily be applied to fields like physics or engineering, it finds a very clear expression in acarology. The world of mites is a seemingly small but epistemologically boundless cosmos: a universe difficult to see, difficult to understand, difficult to define, and difficult to control. The world of these tiny creatures is a realm that science touches with curiosity, with new mysteries constantly being revealed. Therefore, the magnitude of the small, the density of the unseen, the proliferation of ignorance born in the pursuit of knowledge, make acarology a living example of the "frontier" metaphor.

In this context, acarology transcends being merely a discipline limited to the study of microscopic organisms; it offers a window to the nature, limits, and knowledge-producing processes of science. Each new discovery increases our awareness of the complex and ever-expanding universe of both small organisms and human knowledge. This article examines how acarology, through its diverse nature, technical difficulty, and ecological and molecular complexity, exemplifies the notion of science as an endless frontier.

By approaching acarology through a conceptual and disciplinary perspective, this paper highlights why persistent taxonomic uncertainty, methodological difficulty, and emerging ecological complexity constitute inherent features of the field, rather than issues in need of resolution.

DergiPark AKADEMİK

METHODS

This study is a theoretical and synthetic review that reinterprets the metaphor "science as an endless frontier" in the context of acarology. To this end, a comprehensive search was conducted through Web of Science, Scopus, ScienceDirect, Springer Nature Link, JSTOR, Google Scholar, and ResearchGate. The search of scientific literature examined the fundamental research axes of acarology—species diversity, microscopic morphology, ecological functions, molecular data, and phylogenetic relationships—while a broader search of philosophical literature included studies of scientific limits, epistemic and methodological limitations, and unpredictability. Based on both classical and contemporary sources, this search was conducted with the aim of achieving interdisciplinary coherence, and the information obtained was analysed by dividing it into thematic subheadings according to its content. Since the study is not experimental, the inferences are based not on direct observational evidence, but on conceptual analyses of the literature. In this context, the study is an interpretive and synthetic review of established knowledge rather than the presentation of new empirical findings.

RESULTS

The discussion of the nature of acarology begins with the theoretical foundations of acarology as a scientific discipline, its historical development, and its relationships with other fields; and is followed by a discussion of what common-sense assumptions and scientific falsifiability mean for this area of study.

The section entitled "The inexhaustible nature of discovery" examines the extraordinary diversity of mites and the epistemic tension created by the continuous expansion of knowledge of the subject. The following section, entitled "The invisible universe of mites", examines the effect of constantly improving technological tools that enable the discovery of increasingly minute morphological structures, expanding and redefining the boundaries of knowledge.

Subsequent paragraphs examine the complexity, unpredictability, and multi-layered interaction networks stemming from the nature of the discipline, under the headings "The open-ended nature of mite ecology" and "New horizons opened by molecular data". In the section entitled "Fallibility, limitations, and methodological vulnerabilities in acarology", it is shown that knowledge production in acarology is fallible at both the technical and theoretical levels; and that methodological choices often become critical factors that determine the boundaries of the discipline. In the section entitled "Boundary intersection in acarology: internal and external dynamics", it is shown that the discipline's unique internal limitations interact with external limitations stemming from the socio-scientific environment; thus, it is emphasised that acarology is a field that constantly evolves in contact with the boundaries of science.

In the section entitled "Psychology of the endless frontier", the cognitive and emotional dimensions shaping the acarologist's engagement with an ever-expanding field of inquiry are examined, with particular emphasis on how uncertainty, scale, and incompleteness influence scientific motivation and perception. "Acarology as an epistemic practice: systematics as historical reading" conceptualises mite systematics as an interpretative and historically grounded scientific practice, in which the history of nature written at the micro-scale is reconstructed through a palaeographic reading of morphological characters. This perspective is then extended in "Mapping the unfinished micro-scale world: cartography and the endless frontier", where a cartographic metaphor is used to frame acarology as an open-ended process of knowledge production. Here, the micro-scale world is continuously redefined rather than definitively mapped.

1. Acarology as a science: its theoretical, historical, and disciplinary position

Before beginning a discussion of the independence and position of acarology, it is first necessary to understand the nature of biology as a science. Ernst Mayr, a prominent philosopher and biologist of biology, views biology as an autonomous science. According to Mayr (1997), biology can be considered a "provincial science" because life as we know it has only existed for 3.8 billion years out of the approximately 10 billion years since the Big Bang. While this historical perspective seems to limit the universality of biology, it is nevertheless true that universal laws of nature are generally found in fields such as physics or chemistry. In biology, however, it is difficult to find absolute laws that are valid in every case, everywhere, and at all times; because biological processes involve historical, environmental, context-dependent, diverse, and complex systems (Mayr, 1997).

Biology is not the same kind of science as physics and chemistry because the phenomena it attempts to explain, such as living organisms, evolutionary processes, genetic structures, and species, cannot be fully understood through physico-chemical reductionism. However, the fundamental principles, structures, and processes of biology (e.g., cellular structure, energy transformation and homeostasis) are universal in nature. This makes biology not only a science specific to this world but also a "science concerning the universal principles of life". If other life forms exist or will exist in the universe, biological principles can be used to understand them as well. Therefore, biology also has the potential to be a theoretically universal science (Mayr, 1997). At best, it would be appropriate to consider biology as a "special science" with a mixed, or dual status.

This brief discussion of biology's epistemic status provides the conceptual background necessary to situate acarology within the broader structure of the biological sciences. Acarology thus constitutes a highly localised sub-discipline within biology. Nevertheless, it also has the potential to produce significant theoretical contributions in terms of testing universal biological principles and revealing their limitations. Although acarology is largely descriptive in nature, it also produces powerful explanatory models in ecology, evolution, behaviour, physiology, and pathobiology. Here, the descriptive character of acarology is not invoked

as a limitation, but as a foundational strength upon which explanatory and integrative models are built.

In short, acarology is a multi-layered scientific discipline that examines universal biological principles, but works within a locally grounded context. This raises the question of whether acarology constitutes an independent science. Acarology is the branch of science that studies all biological aspects of organisms known as mites, and is positioned as a sub-discipline of zoology (Lincoln et al., 1982; Woolley, 1988; Hoy, 2011; Kaakeh et al., 2025; Merriam-Webster, n.d.). In this respect, acarology can be considered an epistemically autonomous subfield within biology, much like entomology, malacology or ornithology. Thus, while acarology may not always be organised as a formally independent science, it clearly functions as an epistemically autonomous discipline within biology.

From a historical perspective, acarology emerged within the frameworks of zoology, veterinary science (parasitology), and agricultural sciences. In addition, certain mite groups of medical importance have been studied within the domains of medical parasitology and dermatology, further expanding the applied scope of the discipline. Particularly in the context of agricultural pest mites, acarology has historically been considered an applied sub-discipline within agricultural science, especially with regard to integrated mite management and pest control (Zhang, 2003; Hoy, 2011; Dhooria, 2016). For this reason, acarology is a sub-discipline of biology (zoology); however, historically and institutionally, it is a multidisciplinary science with applied branches in plant protection and veterinary medicine. This multiple positioning is a structural feature of the discipline and should not be interpreted as a contradiction, but rather as a form of "plural belonging". Nevertheless, this plurality of institutional and disciplinary locations has at times fostered subtle forms of boundary-making among researchers working in agricultural sciences, veterinary medicine, and basic biological disciplines. This is evident, for example, in the historically persistent dominance of applied and taxonomic orientations within acarology, while evolutionary and theoretical perspectives have gained prominence more gradually (Bruin et al., 1999). Such disciplinary divergences have occasionally fostered forms of epistemic separation within acarological research communities, a dynamic that aligns with established analyses of paradigm-bound scientific practice and boundary-work in science (Gieryn, 1983; Kuhn, 1996). These references are employed not normatively but analytically, in order to frame how disciplinary boundaries and epistemic orientations emerge and persist within scientific fields.

From a philosophical perspective, these processes are not merely social phenomena but epistemic ones, in which each subfield both reflects upon and delimits its own conditions of understanding—an insight central to Bachelard's notion of epistemological obstacles and Gadamer's hermeneutic philosophy (Bachelard, 2002; Gadamer, 2004). In this sense, disciplinary perspectives do not simply compete; rather, they mutually define one another through epistemic differentiation. Approaching acarology with a shared sense of disciplinary belonging—rather than as a fragmented collection of applied or theoretical domains—should therefore be seen as a productive stance. Although strong identities rooted in agriculture, veterinary science, or fundamental biology clearly enrich acarological research, mites cannot be fully understood through any single disciplinary lens alone. Their biological diversity and functional complexity require perspectives that extend beyond the limits of isolated frameworks. Collective and integrative research practices, grounded in mutual recognition rather than exclusion, thus allow acarology to function not only as a plural science, but as a coherent one.

Today, acarology has established itself as a strong scientific discipline based on modern interdisciplinary research methods. Prasad (1982), in his work "*History of Acarology*," describes the historical development of acarological studies conducted in 22 different countries. Krantz and Walter (2009), in their work "*A Manual of Acarology*," present a brief history of the discipline, as in previous editions of the same work. Dhooria (2016), in his book "*Fundamentals of Applied Acarology*," also addressed the historical development of the field. More recently Doğan and Ecevit (2023) and de Moraes et al. (2025) have discussed how the science of acarology emerged as a result of the interaction of cultural and historical factors and how it has reached its current scientific level.

When the history of acarology is examined, it becomes evident that its development has not followed a trajectory strictly parallel or linearly aligned with the major paradigms in biology, such as physicalism, vitalism and organicism. However, acarology does bear traces of overlap with some aspects of these paradigms in certain periods. The earliest stages of acarology were largely consistent with a physicalist and mechanistic scientific perspective; because mites were primarily observed, identified, and classified under the microscope. Indeed, pioneering researchers such as Alfred Nalepa, who focused particularly on gall mites, described numerous species and based their work primarily in taxonomy and descriptive systematics (Doğan and Ecevit, 2023). As knowledge of mites increased, their organ systems, developmental stages, and behavioural characteristics were gradually clarified; this process was carried out primarily within a mechanistic, physical, and descriptive framework.

It cannot be said that a vitalist approach has had a significant influence in acarology; as clear examples supporting a vitalist interpretation of mites have not yet been identified in the literature. Vitalism is mentioned here solely to clarify its absence as an influential explanatory framework in the historical development of acarology.

In contrast, research since the second half of the 20th century has extended far beyond purely morphological descriptions. Particularly with advances in molecular biology, genetics, ecology, and evolutionary biology, acarology has begun to transform into an interdisciplinary field encompassing not only taxonomy and morphology, but also evolutionary, phylogenetic, ecological, and adaptive dimensions. This transformation gained symbolic significance at the 8th International Congress of Acarology in

1990 with the theme "*Modern Acarology*" (Dusbábek and Bukva, 1990).

The work of L. van der Hammen, E.E. Lindquist, B.M. OConnor, and other researchers on homology, common ancestors, phylogenetic relationships, and ecological adaptations, has significantly contributed to acarology moving beyond purely reductionist explanations towards a more holistic and organic perspective. In short, while the theoretical development of acarology has not followed a completely linear or unidirectional path, it can be characterised as having originated within a broadly physicalist framework and remained largely independent of vitalist approaches, converging with principles characteristic of organicist thought.

The integration of modern tools such as bioinformatics, genomics, metagenomics, and microbiome analysis into mite research has transformed acarology into an interdisciplinary, holistic, and evolutionary-ecosystem-oriented science. This broad interdisciplinary nature demonstrates that acarology is not merely about species identification and cataloguing, but also contributes to contemporary biological and environmental science issues such as the evolution of symbiotic relationships, the dynamics of pathogen-host interactions, vector biology, ecological adaptations, and biodiversity conservation. Acarology has become a multifaceted and multidisciplinary science of major significance from the perspectives of basic biology, applied sciences (such as agriculture and public health), and ecology. The minute size and ecological diversity of mites provide the tools for examining a wide range of fundamental phenomena in evolutionary biology.

The conceptualization of acarology in this study can be clearly aligned with contemporary Nature of Science (NOS) models. Notably, the Family Resemblance Approach (FRA) by Irzik and Nola (2011), expanded upon by Erduran and Dagher (2014), offers a comprehensive framework for viewing science as an integrated system of related categories rather than isolated epistemic claims. FRA highlights that science includes aims and values, scientific practices, methodological rules, knowledge structures and social-institutional aspects.

When examined through the Family Resemblance Approach, acarology does not merely represent a specialised taxonomic sub-discipline; rather, it illustrates how the cognitive-epistemic and socio-institutional categories of science interact within a concrete research field. Its aims extend beyond species delimitation to include explanatory coherence and evolutionary integration, reflecting epistemic values such as accuracy, consistency, and scope. Its scientific practices are embodied in classification, comparative morphology, and revisionary systematics, while its methodological dimension is governed not only by technical tools such as microscopy and molecular analysis but also by normative criteria concerning character evaluation, homology assessment, and evidential justification. The knowledge structure of acarology is historically layered and revisable, as taxonomic hypotheses remain open to reinterpretation in light of new evidence. Lastly, the social and institutional facets manifest through nomenclatural regulations, peer review processes, collection management, funding mechanisms, and professional scientific communities that influence the creation and validation of taxonomic knowledge.

By making this theoretical grounding explicit, the present study does not merely illustrate selected features of science through acarological examples; rather, it positions acarology as a case study demonstrating the integrated and systemic character of science as conceptualised in FRA.

2. Questioning common-sense and scientific falsifiability

In every branch of science, there are numerous examples of ideas that were initially accepted as true and based on common-sense, but have later been revised or abandoned as a result of new evidence and refined or improved methodologies (Chalmers, 1999). Acarology is no exception. Because this field is based on the study of microscopic organisms, it has been particularly prone to erroneous assumptions, especially in its early stages, due not only to technological limitations but also to implicit conceptual presuppositions that guided observation and interpretation (explained in more detail in Sections 7 and 8).

Perhaps the most common misconceptions in acarology relate to the identification of species or other taxa. Given the small size of mites, it is hardly surprising that researchers have frequently been misled by superficially distinct morphological differences. Accurate species identification constitutes a fundamental prerequisite for robust scientific inference. Accordingly, species identification represents a critical level within the hierarchy of biological systems and serves as an important prerequisite in many ecological, taxonomic and evolutionary studies (Mayr, 1997). In both early and more recent periods, researchers have sometimes described new species without fully accounting for intra-specific morphological variation, leading to numerous issues with synonymy. The common-sense inference that "apparently different morphology implies different species" has often proven unreliable misleading. This is because age-, season-, and sex-related variation in animals is widespread in animals and requires careful, conceptually informed assessment of such variations (Mayr and Ashlock, 1991).

The application of molecular techniques, the revision of old definitions, the redescription of inadequately characterised taxa, the identification of cryptic species, the recognition of synonyms and homonyms, and the implementation of standardised nomenclatural rules, have all made significant contributions to the conceptual maturation of acarology (Skoracka et al., 2015; Niedbała and Liu, 2023). Every attempt to produce a taxonomic classification represents a hypothesis of relationships, even if that hypothesis is not overtly acknowledged. In this sense, taxonomic frameworks are not merely descriptive but are embedded in broader theoretical commitments that render them open to critical scrutiny and revision. These examples demonstrate the open-ended nature and continuous falsifiability of scientific knowledge, reflecting a constantly evolving

process of understanding rather than absolute truths. Therefore, as Mayr (1997) also states, the term "understanding" is more appropriate here than "knowledge". Thus, the errors and corrections observed in acarology clearly reveal that science is not merely about facts, but rather a constantly questioned, revised, and deepened process.

3. The inexhaustible nature of discovery

One of the fundamental unknowns in acarology concerns the true extent of mite diversity. A widely used method for estimating the overall number of existing species within a taxonomic group is to extrapolate from the temporal pattern of documented species descriptions (Bebber et al., 2007). This approach has a weakness caused by a lack of data (André, 2025), but it nevertheless serves as a useful heuristic for approximating the overall range of mite diversity. As summarised in Table 1, estimates of the number of described Acari species have steadily increased over the past six decades—from approximately 17,500 species in the early 1960s (Wharton, 1964) to about 63,000 species in recent syntheses (Sullivan and Ozman-Sullivan, 2021).

Table 1. Estimates of the number of described species of Acari.

Published source	No of species
Wharton (1964)	~17,500
Krantz (1970)	~30,000
Halliday et al. (2000)	~48,000
Krantz and Walter (2009)	~55,000
Zhang et al. (2021)	~60,000
Sullivan and Ozman-Sullivan (2021)	~63,000
Present work	~65,000

Based on publications in journals indexed *Zoological Record*, including the core acarological journals *Acarina*, *Acarines*, *Acarologia*, *International Journal of Acarology*, *Journal of the Acarological Society of Japan*, *Persian Journal of Acarology* and *Systematic and Applied Acarology*, as well as broader taxonomic journals such as *European Journal of Taxonomy*, *Journal of Natural History*, *ZooKeys* and *Zootaxa*, and selected regional zoology, entomology and systematics journals, it is estimated that approximately 600 new species of mites have been described worldwide each year on average in recent years (Zhang et al., 2021). In light of this sustained taxonomic output, the updated assessment places the current total number of described mite species at approximately 65,000 (present work). Yet, despite this continued growth, the true diversity of mites is widely regarded as far greater (Krantz, 1978; Krantz and Walter, 2009; Sullivan and Ozman-Sullivan, 2021, 2023). Although deriving an exact global annual total from the available literature is challenging, studies such as Halliday et al. (2000), Liu et al. (2013) and Zhang et al. (2021) document thousands of new mite taxa described in prominent journals over the last twenty years, indicating a continuing trend of species discovery. Considering the long-term taxonomic output and the growing taxonomic efforts globally, it is reasonable to deduce that hundreds of new mite species are formally described each year.

The diversity of mites is so vast that the discovery of each new species not only fills a gap in taxonomy but also raises new questions concerning ecological interactions, evolutionary processes, parasitic dynamics and pathogen transmission. In this sense, acarology represents a clear example of the scientific cycle in which answers generate new questions in accordance with a fallibilist understanding of scientific knowledge (Popper, 2005).

When every new species is recognised, the boundary of acarology expands and the number of undefined species increases once again. The advancement of understanding cannot stop the proliferation of the unknown; on the contrary, the unknown reproduces itself every time a new discovery is made. This should not be interpreted as an ontological claim about reality itself, but rather as an epistemological observation concerning the structure of scientific inquiry, and as a consequence of the dynamic and expanding cyclical nature inherent in knowledge itself (Popper, 1962, 2005).

The notion that the growth of what we know simultaneously expands what we do not know aligns perfectly with the thought attributed to Albert Einstein – "*as our circle of knowledge expands, so does the circumference of the unknown*" when understood as heuristic metaphor rather than a literal model of knowledge growth. As new mite species are defined, it becomes clear that the true extent of species diversity is even greater; this shows that knowledge exhibits a fractal, not linear, structure. Hegel's (1807) dialectical approach, "knowledge itself (thesis) contains its opposite (antithesis)", also gains surprising significance in acarology. Therefore, acarology offers a universe that expands as it is explored, and the metaphor of "infinite limits" perfectly reflects this phenomenon.

In this section, the metaphor of "infinite frontiers" is used to illustrate extraordinary richness of mite diversity. This diversity and the accompanying uncertainties stem not only from the number of species but also from the complexity of the microscopic structures of mites and the observational difficulties involved. The next section explores the invisible universe of mites and its impact on scientific research processes.

4. The invisible universe of mites

Because of their minute size, access to the world of mites depends not only on observation but fundamentally on methodology and the epistemic conditions under which observation becomes possible. Since most mites are microscopic, the limits of our knowledge about these organisms are directly shaped by technological capacity. As electron microscopes, light microscopy techniques such as phase contrast and DIC, confocal imaging methods, and other advanced imaging tools develop, previously unknown species, structures, and processes become visible (Fisher and Dowling, 2010; Chetverikov et al., 2015, 2024; Klimov et

al., 2022). Each new discovery reveals complexities that had previously gone unnoticed. This aligns with Ihde's (1990) idea in the philosophy of technology that "technology not only makes certain phenomena visible but also generates new domains of invisibility". From Ihde's perspective, technology changes not the world, but the way we relate to the world. Technological change shifts the boundaries of perception: while rendering some aspects visible, it simultaneously creates new limitations (Ihde, 1990, 2020). This problem is especially acute in the science of taxonomy. When the most modern technology is used in taxonomic research, apparent weaknesses in a previous generation of work become even more apparent, even if they used the best available methods of their time.

The invisible universe of mites can also be viewed in terms of a more nuanced epistemic dimension—the conversion of living, three-dimensional organisms into abstracted scientific representations—beyond the technical limitations imposed by scale and instruments. In acarological publications, mites are most often presented as discrete sets of diagnostic features, graphs, schematic drawings or two-dimensional representations, rather than as dynamic organic beings. Although these representations are essential for description, communication and comparison, they unavoidably filter biological reality through analytical reduction and established standards of depiction. In this process, spatial continuity is converted into standardised descriptive elements, and some structures are highlighted while others remain secondary or are completely ignored. This viewpoint is in line with more general discussions in the philosophy and history of science that highlight the fact that scientific representations and images serve as epistemically mediated constructs shaped by disciplinary practices and representational choices, rather than as impartial mirrors of nature (Daston and Galison, 2010). Similarly, Rheinberger's (1997) concept of "epistemic things", which holds that the objects of scientific knowledge arise within particular experimental and representational contexts, is consistent with the distinction between the biological organism and the scientific object made visible through analytical practices. From this perspective, the invisibility of mites is not limited to their small size or to the constraints of observation, but also includes aspects of biological organisation that are simplified or omitted through standardised modes of scientific representation. Such abstraction is a necessary condition for producing stable, comparable and communicable knowledge across different studies and research contexts (Latour, 1999).

The discovery and development of new tools and techniques have revolutionised science; however, in the historical development of biology, no other tool can compare to the transformative effect provided by continuously improved microscopes (Mayr, 1997; Balasubramanian et al., 2023). Advances in microscopic technology have also enabled the observation of mites at an astonishing level of detail. In addition, the development of extraction devices developed by Berlese (1905) and Tullgren (1918) has substantially improved the collection of particularly soil-dwelling mites. These devices, or their more advanced modifications, are still widely used today for the same purpose. Furthermore, the development of effective slide-mounting media has had a profound impact on the study of mites and other microarthropods, significantly enhancing the quality and reliability of morphological investigations (de Moraes et al., 2025). Beyond their technical contributions, these innovations have reshaped the conceptual framework of acarology, influencing not only what can be observed, but also how biological meaning is constructed from those observations—thereby shaping the ways in which scientific knowledge accumulates and deepens.

While scientific knowledge, which can be described as "repositories of information," deepens in layered complexity with the expansion of technological capacity, acarology has also transformed into a dynamic field that is directly driven by this progress, constantly restructuring itself. The enigmatic world of mites reminds us that seeing something is not the same as understanding it; understanding something reveals aspects of it that we had not noticed before.

In light of their minute structures and observational complexity, the microscopic universe of mites demonstrates that merely visualising them is only a starting point; true understanding entails revealing previously unseen, multilayered aspects at both structural and functional levels. Mites inhabit a world that is highly complex and unpredictable, not only morphologically but also in terms of their ecological interactions. The following section focuses on the multiplex roles of mites within ecosystems and the open-ended nature of their ecological interactions.

5. The open-ended nature of mite ecology

Mites have extremely complex ecological roles within ecosystems. In addition to free-living species, diverse modes of coexistence such as predator-prey and host-parasite relationships combine with population dynamics and resistance and buffering mechanisms (including host defensive responses, population-level adaptive resistance and context-dependent ecological modulation of interactions) to form exemplary cases of this intricate network of interactions (Doğan et al., 2023). Such relationships are so fine-scaled and complex that a change in even a single variable can have unpredictable effects on the entire system (Landi et al., 2018; Stella et al., 2018). Importantly, these interactions are not fixed properties of species themselves but are contingent upon ecological context, rendering their outcomes inherently variable.

Interactions involving mites within ecosystems are often more complex than they first appear and are sometimes difficult to characterize, underscoring the multifaceted and adaptive dynamics typical of complex systems (Halliday, 2019). A single mite species may associate with multiple hosts; a host can harbour numerous mite species; and the same pathogen can be carried by dozens of mite species at varying rates (Walter and Proctor, 2013; Klimov and He, 2024; Yin et al., 2025). This web of multiple, non-linear and context-dependent relationships exceeds the descriptive scope of Tansley's (1935) classical concept of the "ecosystem" and corresponds more closely to what Levin (1998) has defined as "complex adaptive systems", in which collective behaviour emerges from interacting components rather than from linear causation.

The temporal and spatial distributions of species further deepen this within-ecosystem complexity. Certain species may concentrate in different habitats throughout the year, while seasonal cycles and geographical differences can alter both the roles of species and the nature of their interactions (Candolfi et al., 1992; Illig et al., 2010; Gergócs et al., 2018; Chen et al., 2024; Kamczyc et al., 2024; Nichol et al., 2025). When these dynamics are revealed through long-term field observations, relationships initially interpreted as stable are frequently reconfigured, revealing additional layers of interaction and producing outcomes that were not anticipated by earlier models.

Taken together, these characteristics underscore the fundamentally provisional nature of ecological explanations in acarology. Cause-effect relationships observed under specific conditions rarely retain their explanatory power when transferred across habitats, seasons or community structures. Feedback loops involving predation, parasitism, resistance and population regulation further complicate this picture by continuously modifying the very conditions under which interactions occur, preventing convergence toward a single, stable equilibrium (Holling, 1973).

The unpredictability inherent in such complex adaptive systems makes it difficult to fully forecast ecosystem behaviour (Levin, 1998). When Einstein's metaphor of the "boundary line expanding as science advances" is considered alongside ecological systems theory, it becomes clear why acarology constitutes an epistemically open-ended discipline. The open-ended nature of mite ecology does not arise only from insufficient data, but from the intrinsically dynamic, relational and continually reorganising structure of ecological systems themselves. The uncertainty arising from this multifaceted ecological structure is not limited to ecological data, whether field-based or laboratory-based. Molecular data further deepen and reconfigure ecological uncertainty–a theme explored in the following section.

6. New horizons opened by molecular data

The transformation created by molecular technologies in acarology is not limited to increasing the accuracy of species identification but also creates a multi-layered field of knowledge that redefines the evolutionary history of mites, mite-microbiome-host interactions, symbiotic relationships, and pathogen carrier capacities. DNA barcoding, mitogenomics, whole genome sequencing, and metagenomics approaches are yielding significant results, particularly in the resolution of species complexes, the separation of cryptic species, and the clarification of phylogenetic relationships, while RNA-seq has made important contributions to understanding gene expression patterns and functional differentiation among taxa, particularly in developmental, physiological and symbiotic contexts (Hebert et al., 2003; Kress and Erickson, 2012; Pepato et al., 2010, 2018; Pepato and Klimov, 2015; Klimov et al., 2018, 2023; Zhang et al., 2019; Arribas et al., 2020; Xiong et al., 2022).

Molecular data reveal that mite genome sizes can vary significantly depending on lifestyle and evolutionary adaptations (Yang et al., 2025), providing a fundamental framework for interpreting genetic mechanisms related to feeding strategies, symbiont associations, and the microbiome; and simultaneously reshaping ecological and epidemiological knowledge (Bonnet et al., 2017; Brenner et al., 2021; Liu et al., 2021; Brückner et al., 2022; Klimov et al., 2022; Merlin et al., 2023; Zhong et al., 2024).

In recent years, it has become increasingly clear that the microbiome structure of mites can be crucial for both physiology and host adaptation (Merlin et al., 2023; Xie and Zhang, 2023). Evolutionary divergence in genome size (Yang et al., 2025) is understood to provide the background for understanding the genomic basis of these microbial associations. These molecular approaches now make it clear that it is no longer sufficient to consider only the mite itself; rather, the mite-microbiome-host triad must be evaluated as an integrated unit. Thus, the system reproduces, at the molecular level, the characteristic features of complex adaptive systems described by Levin (1998).

On the other hand, phylogenomic data can also shed light on the evolutionary history of viruses and bacteria carried by mites (Guo et al., 2020, 2021). This situation raises new avenues of research regarding the origin and evolution of zoonotic and vector-borne diseases, which should be addressed through comprehensive phylogenic and metagenomic studies rather than case-based microbiome and pathogen identification.

Scientific knowledge is not a linear accumulation, but rather a layered structure that constantly reconstructs itself, expanding from one fragile equilibrium to another. This stratification of knowledge, parallels Derrida's (1967) perspective that a text cannot be reduced to a fixed and singular field of meaning, and each new piece of data produces a new meaning and a new field of interpretation. The expansion of molecular data, instead of narrowing the boundaries of explanation, leads to the continuous redrawing of these boundaries in an ever-expanding manner. Each genomic dataset gives rise to new fields of interpretation alongside the solution of a problem; this transforms molecular acarology into an inexhaustible field of research.

In short, molecular information is not only a tool for confirming existing knowledge, but also an epistemic catalyst that leads to the formation of new theoretical frameworks for mite ecology, evolution, and the biology of mite-microbiome-host relationships. The molecular approach constitutes one of the most powerful symbols of the open-ended nature of acarology. Phylogenetic studies allow us to produce increasingly detailed phylogenetic trees, but the holistic evolutionary panorama formed by these trees often remains unclear. Advances in molecular and genomic research have significantly increased the knowledge production capacity in acarology, but the accuracy and interpretability of the resulting data are still hampered by observational, methodological, and cultural limitations. As Mayr (1997) puts it, "*while we have identified many trees, we have not yet seen the forest*".

7. Fallibility, limitations, and methodological vulnerabilities in acarology

Scientific production is influenced by researchers' value orientations, choices, and ethical responsibilities, as well as societal structures; therefore, the potential for error is an inherent feature of scientific processes (Ravetz, 1996). Although the domain of scientific knowledge continuously expands, it operates within certain "limits of fallibility" due to researcher-related constraints, organisational and institutional shortcomings, methodological deficiencies, and inevitable human errors (Shiffrin et al., 2018). These limitations are particularly pronounced in the field of acarology. In both observational and analytical processes, technical and methodological constraints become critical factors directly shaping the accuracy and reliability of the knowledge produced.

The limits of human vision and cognition become particularly evident in this field. The microscopic size of mites and the limited number and quality of diagnostic characters, as well as the high phenotypic plasticity of many characters, make morphological diagnosis difficult (Ovalle et al., 2020). In addition, uncertainties or minor deviations in homology determination can lead to errors in character coding and shifts in topologies produced by combined morphology-molecular analyses (Pepato et al., 2010). In morphologically challenging groups such as Tydeoidea, Raphignathoidea, or Eriophyoidea, the researcher's lack of experience can lead to erroneous interpretations (de Lillo et al., 2010). Accurate evaluation of taxonomically important characters such as dorsal and ventral setal arrangements, idiosomal striations, gnathosomal structures, and leg chaetoxy structures requires advanced technical expertise. Inadequate use of DIC or other contrast-enhancing techniques can reduce the visibility of these critical micromorphological characters, leading to erroneous taxonomic and phylogenetic interpretations.

Lack of standardisation in field studies and laboratory procedures is also significant sources of error. Variability in sampling protocols, non-standardised terminology, failure to account for differences in ontogenetic stages, incorrect sequence labelling, improper storage of materials, failure to ensure continuity in specimen handling, and absence of standardised or verified values for metadata fields, also weaken data integrity (de Lillo et al., 2010; Gonçalves and Musen, 2019; Stenger and Skvarla, 2022; Caliskan et al., 2023; Doğan, 2025; Pešić et al., 2025). In addition, institutional limitations such as poor quality light microscopy equipment, restricted access to collection materials, inadequate funding and lack of support staff suffered by research institutions (Dupérré, 2020) can further compromise the accuracy of species identifications and the reliability of revision studies.

In addition, methodological problems such as inadequate literature review (e.g., overlooking previous species descriptions, revisionary studies, nomenclatural changes, and distribution and ecological information), lack of standardisation of drawings (e.g., non-conformity in viewpoint and drawing perspective, overly stylised or schematically presented details), incomplete measurements (e.g., failure to clearly specify the measurement method, omission of critical morphometric characters, failure to specify or insufficient sample size), or incorrect identification and naming of taxa (e.g., insufficient adherence to ICZN rules, lack of diagnosis, errors in terminology and character descriptions, failure to consider intraspecific variations) also undermine the integrity of scientific knowledge. All these factors clearly demonstrate that knowledge production in acarology is closely related to fallibility at the individual, methodological, and institutional levels. They also underscore the indispensable need for critical evaluation mechanisms, including re-description, comparison of type or museum materials, and verification of characters.

In acarology, the accuracy and reliability of knowledge production are not limited solely by observational and methodological constraints; they are also shaped by the internal and external limitations surrounding scientific practice. Therefore, the technical and methodological challenges discussed in this chapter, when considered within an epistemological framework, make it possible to understand the limitations arising from the interaction of both internal (methodological and perceptual) and external (socio-political, institutional, and economic) dynamics in acarology.

8. Boundary intersections in acarology: internal and external dynamics

Science can be said to possess both internal and external boundaries. Internal (intrinsic) limits arise from science's own methods, tools, theoretical frameworks and perceptual or technical capacities. Science advances only to the extent permitted by its internal structure. External (extrinsic) limits, on the other hand, arise from science's contact with external factors such as society, ethics, economy, nature, technology, politics, and culture, and are considered as limits that guide or constrain scientific production (Musametov, 2022; Ateş et al., 2023).

Internal limitations in acarology arise from the very nature of the field. Chief among these are the dependence on extremely small morphological structures, the restricted resolving power of light microscopes, the ambiguity of the species concept, the high variability of characters, and the strain on the researcher's perceptual capacity when examining micro-details (de Lillo et al., 2010). Rather than slowing down the discipline's progress, these limitations often create a "dynamic of advancement" that paves the way for the development of new techniques, such as serial blockface scanning electron microscopy (SBF-SEM), confocal laser scanning microscopy (CLSM), DIC and phase-contrast microscopy (Fisher and Dowling, 2010; Chetverikov et al., 2015; Bolton, 2022; Guo et al., 2026).

External boundaries in acarology are mostly related to the socio-scientific environment. Factors such societal failure to understand the economic importance of mites, difficulties in access to type and museum materials (Dupérré, 2020), the incompleteness or lack of national collections (Doğan, 2019), obstacles to specimen transfer arising from legal regulations, the shift of academic priorities towards more popular fields of study (Löbl et al., 2023), and other

taxonomic barriers (Engel et al., 2021) directly affect the direction and pace of research. The nature of acarological research is inevitably influenced by its societal and economic context. It may be difficult to justify devoting resources to an esoteric study of the higher level phylogeny of Arachnida in a community where there is an urgent need for tactical work on pest management. An individual acarologist may come under pressure to publish short-term studies of a local fauna to meet a contractual deadline, instead of attempting a comprehensive global revision of a whole family. However, these external boundaries can be redefined through new collaborative projects, biosecurity regulations, digitised collections, and innovative taxonomic arguments based on cyber infrastructure (Wheeler et al., 2004). These external pressures need not be seen as limitations to science but as opportunities. For example, the international trend towards increasing biosecurity regulations creates an increased need for taxonomic research in groups that contain economically important species.

In this respect, acarology can be defined as a field where both internal and external boundaries intersect and mutually shape each other. From the perspective of the Family Resemblance Approach to the Nature of Science (Irzik and Nola, 2011; Erduran and Dagher, 2014; Kaya and Erduran, 2016), these internal and external boundaries reflect the interplay between scientific practices, epistemic values and socio-institutional structures. Thus, acarology serves as an illustrative case where the cognitive-epistemic dimensions of science are inseparable from their institutional and socio-political contexts.

9. Psychology of the endless frontier

When an acarologist works at his/her microscope, his/her attention is focused on a tiny spot of light, to the exclusion of almost all other distractions. Within that spot of light, he/she concentrates on the details of minute structures that may be 20 micrometres long or less. After a day of intense concentration, he/she assembles the information from hundreds of structures into the description of a species and spends another day making illustrations. He/she repeats all that detailed work ten, twenty, or even more times to prepare a revision of a genus and prepares the results for publication.

The acarologist experiences a moment of excitement when he/she finds a structure that has not been studied before, perhaps because older microscopes were not good enough to resolve it. He/she uses that structure to sort his/her new species into groups and prepares a classification of subgenera or species groups. But then excitement turns to despair when he/she realises that all the old descriptions of species in this genus do not include information about the new structure, so all the old work must be done again. The frontier of knowledge has not come any closer but is actually further away than it was before.

The taxonomic revision of a genus represents good scientific progress, but there are perhaps 20 more genera in the family, and 500 more families that he/she has not studied at all. The task ahead appears endless.

The science of acarology depends on a detailed study of the extremely small (a mite in particular), with simultaneous awareness of the extremely large (mites in general). This unusual combination of psychological pressures has been identified in other fields. Astronauts are required to spend days or weeks confined in a small capsule with very little freedom to move around, while paying close attention to a multitude of precise tasks. Claustrophobia is an obvious risk and must be managed. But the astronaut is also aware of being exposed to the infinite expanse of space. The psychological effect of that exposure has been called the "*Black Abyss Syndrome (ABS)*" (Ihor, 2025). Weibel (2020) referred to this phenomenon as the "*Ultraview Effect*" and described it as "*a very real sense of the limitations of what we know compared to the vastness of what we don't know*". The effect of that phenomenon in acarology is to "humble, inspire, and unite" (Ihor, 2025) its practitioners, as clearly shown by the modern trend towards multi-national teams of authors in acarological publications.

Viewed from this perspective, the psychological difficulty confronted by the acarologist is akin to that of the astronaut who must confront the endless emptiness. Just as the enormous calm of space could provoke the ABS, so too does the persistent minuteness of mite morphology present the acarologist with an ever-broadening frontier of doubts. Whether facing the boundless expanse of space or the intricate details of the microscopic world, investigators encounter a shared truth: the further we delve into it, the more elusive the limits of knowledge become. This, in a way, shows that science is not something that can be reached, but rather a constantly shifting horizon.

From this standpoint, the acarologist is confronted with a further, often unarticulated paradox. While working on organisms far smaller than a point in ordinary perception, he/she may forget that his/her own position in the world can, under a different scale, appear equally negligible. This consciousness does not require remarkable experiences or cosmic travels. A simple shift of perspective, such as viewing the earth shrink from the window of an aircraft, illustrates how cities disintegrate into abstractions and individuals into invisible points. However, this perceptual reduction does not imply that it is insignificant. Conversely, revolutionary scientific and intellectual advancements frequently emerge from individuals who, on any cosmic or societal scale, may seem tiny, yet operate at the margins of knowledge where paradigm changes become conceivable (Merton, 1973; Kuhn, 1996). Confronting enormity, whether macroscopic or microscopic, should not lead to sentiments of impotence, but rather to disciplined humility linked with responsibility. In this sense, the endless frontier of acarology does not lessen the investigator's role; rather defines it.

10. Acarology as an epistemic practice: systematics as historical reading

Despite the fact that mite systematics, similar to other branches of systematics, is frequently regarded as a predominantly descriptive practice, occasionally even as a form of rote or mechanical activity (see Mayr, 1982), this

perspective fails to acknowledge the epistemological profundity of the discipline. In reality, the systematist does not merely describe an organism; rather, they interpret a text seemingly written layer by layer by evolutionary time itself. In this respect, a meaningful analogy can be drawn between the acarologist and the palaeographer working on medieval manuscripts. Just as the palaeographer painstakingly deciphers palimpsests that have been erased, scraped, and overwritten, the acarologist attempts to read a "biological text" through shields, types of setae, and chaetotaxy. In this paradigm, morphological details supersede letters, combinations of characters substitute for sentences, and the species description itself becomes the text.

This act of reading serves as both an exercise in objective data recording and an interpretive endeavour. Morphological structures bear traces not only of the extant organism but also of its evolutionary past (Simpson, 1961; Wiley and Lieberman, 2011). Systematics is essentially positioned as a historical science by the notion that phylogenetic traits serve as carriers of historical information and that this information must be evaluated and reconstructed (Wiley and Lieberman, 2011). In this way, the mite systematist reconstructs a biological story by understanding variations, abnormalities, and morphological inconsistencies rather than reading the organism alone. Systematics, therefore, should be viewed as a historical and interpretive scientific activity rather than as a static practice of description, naming, and classification.

The proposition that "the acarologist does not merely describe mite species but deciphers a palimpsest written by evolution" repositions systematics as a living, open-ended, and meaning-generating field of inquiry. From this perspective, acarology can be conceived not merely as a technical area of expertise, but as an effort to read the history of nature written at the micro-scale.

11. Mapping the unfinished micro-scale world: cartography and the endless frontier

In early maps, unknown regions were often marked with images of fear, such as monsters or words like "*hic sunt dracones*", showing that they were seen as dangerous. As scientists learned more, this fear changed. The unknown stopped being frightening and became a place of discovery. In this sense, the map is not a cognitive tool that suppresses fear, but one that converts it into curiosity.

The acarologist may be understood in a similar way as a researcher engaged in mapping nature at the micro-scale. Unlike the classical cartographer, however, the primary challenge faced by the acarologist is not unknown geography, but scale itself. Every time we notice a new tiny microscopic detail, we have to rethink the limits we previously set. In this process, morphological characters are not merely descriptive elements; they are structures shaped by evolutionary processes and imbued with historical information, which is reconstructed through systematic analysis (Wiley and Lieberman, 2011).

This means that when systematist is studying mites, "unknown species" are not truly empty categories. Instead, they look like areas that might be full, but aren't fully clear yet. The description of a new species does not mean the existing taxonomic framework is complete; it means that the map needs to be redrawn. In this context, boundaries are not fixed lines, but temporary points of reference that change as more data is collected.

From this point of view, the acarologist does not create a final map. Instead, they work like a cartographer who keeps discussing the size of the map with each new observation. The phrase "acarology is cartography under a microscope" should therefore be understood not as a poetic metaphor, but as a way of thinking about the ongoing and unfinished process of creating knowledge about mite systematics.

The palaeographic and cartographic analogies discussed above are not merely ornamental metaphors; they form components of a broader intellectual framework aimed at understanding the mode of knowledge production in acarology. The emphasis here is on the inherently open-ended, expansive, and difficult-to-complete nature of acarology as a scientific field.

Acarology is a way of doing research that looks at very very small parts of nature at the micro-scale. Its fascination stems from our amazement at the variety of life on earth. However, we initially experience an intellectual unease that arises from the limitations of our own mind. In other words, we are confused because we know our own mind cannot really understand it. This is followed by an irresistible, immense excitement and passion for discovery.

When we consider this, we should not think that knowledge about acarology is something we can be sure of or that it is complete. Instead, we should think of it as a research area that keeps on changing. This means that the things we know keep on moving and changing as we learn more. The uncertainty that a palaeographer feels while deciphering a palimpsest or a cartographer redrawing a map is not a sign of a lack of skill in acarology or any other discipline, but a natural part of a productive condition of knowledge itself. Acarology, therefore, should be conceived not merely as a collection of technical specializations, but as an endless frontier of inquiry into nature's history written at the micro-scale, a history that resists complete and final interpretation.

CONCLUSION

Du Bois-Reymond (1872), in his renowned essay, adopted a pessimistic stance and underscored the limited capacity of the human intellect in the face of nature by declaring, "*Ignoramus—Ignorabimus*" (*We do not know—We will not know*). Du Bois-Reymond's stance was criticized by a number of scholars, who argued that all of the problems he had proposed were either resolvable in principle or already very close to being solved (Mayr, 1997). Among the most prominent opponents of Du Bois-Reymond's view was Hilbert (1935), who, with the dictum "*Wir müssen wissen—Wir werden wissen*" (*We need to know—We will know*), articulated a direct rebuttal to Du Bois-Reymond's claim

(McCarty, 2005). The question of whether scientific questions can truly be solved or whether they inherently remain within certain limits has been discussed from different perspectives by thinkers such as Barrow (1998) and Rescher (1999). Although overly optimistic views arguing that science can answer all kinds of problems are frequently encountered, many scientists are aware that this does not fully reflect reality. Just as Du Bois-Reymond underestimated the capacity of science, some researchers have tended to overestimate it (Mayr, 1997).

Du Bois-Reymond's arguments highlight the question of whether science has inherent limits. Some philosophers of science argue that it is possible to consider these limits not merely as an abstract concept, but as an experiential and dynamic structure. This perspective is meaningful not only for large, abstract scientific enterprises, but also for disciplines dealing with microscopic organisms. Acarology, in its study of microscopic organisms, reveals a small-scale world that nonetheless opens vast epistemic horizons. This field points to an ontological infinity in its species diversity, a phenomenological depth in its microscopic nature, a systemic clarity in its complex ecosystem, a data-driven limitlessness at the molecular level, and a philosophical infinity in its necessary deficiencies in knowledge production. Every scientific discovery brings with it new gaps and unknowns. Science here is not about crossing a boundary line, but about experiencing the constant shifting of that boundary line.

Acarology is an embodiment of the idea of the infinity of science. Therefore, it can be seen not only as a biological field of study, but also as a living example of the "never-ending quest" metaphor discussed in the philosophy of science. Mites may be small, but their potential to expand the horizons of science is immense.

This observation is not unique to acarology. Many disciplines, such as physics, astronomy, or the social sciences, constantly encounter new unknowns in their scale, methods, and conceptual frameworks. Whether it is a field that studies microscopic organisms or a discipline that explores the depths of the cosmos, science constantly encounters new unknowns and expands its horizons as its existing boundaries shift.

Authors' contributions

Salih Doğan: Conceptualization, theoretical framework development, data curation, writing - original draft, writing - review & editing. **R. Bruce Halliday:** Supervision, conceptual input, writing - original draft, writing - review & editing.

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