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To cite this article: Jindong Zhang *et al* 2025 *Bioinspir. Biomim.* **20** 026014

IOP Publishing Bioinspir. Biomim. 20 (2025) 026014 https://doi.org/10.1088/1748-3190/adaff6

Bioinspiration & Biomimetics

OPEN ACCESS

RECEIVED
4 December 2024

REVISED
16 January 2025

ACCEPTED FOR PUBLICATION
29 January 2025

PUBLISHED
12 February 2025

PAPER

Biomimetic tools: insights and implications of a comprehensive analysis and classification

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Keywords: biomimicry, biomimetics, biologically inspired design, process, tool, AI, innovation

Supplementary material for this article is available online

Abstract

Biomimetics as the transdisciplinary field leveraging biologically inspired solutions for technical and practical challenges has gained traction in recent decades. Despite its potential for innovation, the complexity of its process requires a deeper understanding of underlying tasks, leading to the development of various tools to aid this process. This study identified an inventory of 104 tools used in biomimetics, of which 24 have been classified as fully accessible, functional, and ready-to-use biomimetic tools. Additionally, it provides definitions and evaluation criteria for biomimetic tools, offering a structured approach to tool assessment. The 24 tools have been assessed based on ten criteria in a qualitative and quantitative analysis yielding an overview of their typology, accessibility, stage of development, and other key characteristics. Patterns of the typology development of tools over time revealed a trend towards integrating computational methods and artificial intelligence, thereby enhancing the tool's functionality and user engagement. However, gaps in tool functionality and maturity, such as the lack of tools designed to support technical processes, the absence of tools tailored for solution-based approaches, and insufficient evidence of successful tool application, highlight areas for future research. The study results underscore the need for empirical validation of tools, and research into the effectiveness of holistic tools covering multiple stages of the biomimetic process. By addressing these gaps and leveraging existing strengths, the field of biomimetics can continue to advance, providing innovative solutions inspired by biological models.

1. Introduction

Earth's first biological organisms formed 3.8 billion years ago and have since diversified, giving rise to millions of species through an evolutionary process of trial and error, leading to a multitude of adaptations. Diverse species and their astounding adaptations offer a vast source of inspiration for product and process design, which forms the fundamental motivation for biomimetics (Vincent *et al* 2006). The concept of exploring nature as an extensive repository for potential solutions or ideas is associated with various terms, including biomimetics, bioinspired design, biomimicry, and bionics, etc, each with its nuanced implications and focus (ISO/TC266 2015, Speck *et al* 2017). These forms of bioinspiration have had widespread research applications in fields such as aerospace, robotics, and architecture (Vincent *et al* 2006). Well-known successful examples include VELCRO® (Velcro IP Holdings LLC 2024), gecko tape (Geim *et al* 2003) or using the lotus effect for self-cleaning surfaces (Cheng *et al* 2006).

Despite its high potential for innovation and inspiration, the application of biomimetics is complex, including multiple steps and lacking universal guidelines (Vincent *et al* 2006, Lepora *et al* 2013). In 2014, it was stated that for the transition of the promising paradigm of biologically-inspired design into a scalable and repeatable methodology, amongst other scientific challenges, it was necessary to develop more computational tools (Goel *et al* 2014). Furthermore, interdisciplinary communication and synergistic collaboration among biologists, designers, and engineers with varied professional backgrounds are required (Speck and Speck 2008, Schöfer *et al* 2018, Chirazi *et al* 2019, Graeff *et al* 2021b). An in-depth understanding of biology is crucial and must not be overlooked in biomimetic projects, and the extensive involvement of biologists is of utmost importance in having a well-founded basis of biological research for the biomimetic process (Snell-Rood 2016, Graeff *et al* 2019). To facilitate the implementation and interdisciplinary collaboration of biomimetics, researchers and practitioners have developed a variety of tools for the biomimetic development process (Fayemi *et al* 2017). Even though tools have been developed for decades and the term is widely used, a clear definition is not an easy task. To suit the purpose of this study, a 'biomimetic tool' is defined in this paper as *an entity characterised by operability and interactivity, with the capability to produce certain outputs. The tool is designed with the intention of assisting users in executing partial or complete steps within the biomimetic development process.* This definition may also encompass tools developed within other bioinspiration fields, such as those utilising biomimicry terminology. Such tools are considered biomimetic tools in this study if they support or assist in fulfilling the biomimetic processes outlined in the VDI 6220 (2023). Excluded are purely theoretical biomimetics publications that do not propose operational tools, as well as conceptual frameworks for tool development that have not resulted in functional tools, empirical knowledge from biomimetic case studies, and tools that are not available in English.

Wanieck *et al* (2017) found that biomimetic tools were not commonly used even though being created to aid practitioners. Their study presented an overview and classification of 43 biomimetic tools to stimulate the implementation of biomimetics. Since then, some tools have become obsolete, others have been updated or replaced, and new tools have emerged. The evolution of tools used in biomimetic practice is linked to (a) a higher awareness of open source possibilities, leading to more open source tools, (b) the growth of artificial intelligence (AI), leading to several new tools, and (c) the improving conscious on sustainability aspects, as seen in new sustainability assessment tools (Shyam *et al* 2019, Jatsch *et al* 2023, Mas'udah and Livotov 2024). The large variety of tools hinders the effective selection and application of tools in product development and research within the biomimetics field, as users are not guided in a decision-making process (Graeff *et al* 2021a). The first attempts to achieve this can be seen in the preliminary decision tree for choosing specific tools (Fayemi *et al* 2017), or in other literature (Fu *et al* 2014, Beismann and Sauer 2018). Furthermore, while standards or technical guidelines such as ISO 18458:2015 and VDI 6220 Part 2 (Wanieck *et al* 2022) provide descriptions of the biomimetic process, there is a noticeable gap in suggestions of tools that support the individual steps of the process, thus complicating the identification and implementation of such tools. This gap highlights the need for an updated systematic overview of the biomimetic tools to aid researchers and practitioners in their ongoing biomimetic projects. The primary objective of this study is to provide a summary and assessment of the biomimetic tools that are functional and currently available as of June 2024 to enable interested parties to look up and choose tools according to their needs. It should be noted that most accessible tools are of academic origin; many industrial tools, processes and applications remain proprietary, potentially introducing an academic bias. Within this paper, the authors seek to (a) develop a clear definition for tools used in biomimetics; (b) provide an overview of the current biomimetic tools' landscape; (c) establish and apply qualitative and quantitative assessment criteria to review biomimetic tools; and (d) to highlight gaps in available tools and their capabilities, making suggestions for future tool development.

2. Methodology

2.1. Identification of biomimetic tools

To collect biomimetic tools that meet the definition provided in this study, the data collection method from the literature (Wanieck *et al* 2017) has been used and adapted. Table 1 summarises the used databases, and the keywords used for the search.

The identified literature was then screened based on titles and abstracts, retaining papers related to tools. The items (candidates with the potential to fit the definition of a biomimetic tool) mentioned in these papers were recorded on a spreadsheet. The search was further expanded through related literature (citations and references), authors, and research labs using a snowballing technique, which included manual snowballing and the use of online platforms such as Connected Papers (connectedpapers.com) and ResearchRabbit (researchrabbitapp.com) to find relevant literature.

The literature research has inherent limitations, such as potential selection bias and language restrictions, and cannot exhaustively identify all biomimetic

Table 1. Databases and search terms used for literature research. Each search query was formed by combining one term from section A with one term from section B, using the Boolean operator AND. All possible combinations of terms from both sections were used for each database accordingly. Note that the term 'bionic*' was not used as one of the search keywords as this study's scope is to review tools within the biomimetic/biomimicry framework.

Databases Used	Search Keywords Combination (section A AND section B)		
Google Scholar Scopus Web of Science	Section A	Boolean operator	Section B
	'biomim*' 'bio* inspir*' 'natur* inspir*'	AND	'tool*' 'method*' 'framework*'

tools. The final number of items ($n = 104$) was reached after no further potential tools were identified through the methods described above in multiple iterations over a search period of three months. The resulting inventory is as comprehensive as possible within the available resources and capabilities of this study, including temporal and human resource limitations. For an overview of these 104 items, see appendix 2.

Figure 1 demonstrates the biomimetic tool identification and classification scheme. After 104 items had been identified through literature research, they were classified based on a set of inclusion–exclusion criteria. To summarize the classification results, only the 24 tools that are fully accessible, functional, and ready for immediate use are included in further study, other items are classified into their corresponding categories and excluded.

2.2. Biomimetic tool assessment

For the assessment of tools, 10 assessment criteria were established and are explained in table 2. Additionally, an evaluation method for the assessors has been defined, including relevant scales (for detailed information including the full version of the evaluation method and justification of the criteria, please refer to appendix 1). The two co-first authors of this paper are the two assessors of this evaluation process. After completing the assessment through independent rating, they compared and analyzed their results finally sharing them with the other two authors, who concurred with the assessment.

These 10 criteria were established to give an overview of the tools' characteristics and capabilities, which could better help the readers understand the tools. The order of criteria from C1 to C10 follows a logical progression towards a deeper assessment of the identified biomimetic tools. The 24 biomimetic tools were assessed according to these 10 established assessment criteria. Note that some criteria cannot be applied to certain tools because they do not meet the assessment scope of those criteria, such as for C7, only the tools providing biological strategies, defined as the combination of a biological organism or system with a function were assessed. Merely providing a species' name or distribution information does not constitute a biological strategy, as it lacks the requisite functional information. The assessment outcome for those non-applicable situations will be marked as 'NA' (Not Applicable) by the assessors.

Independent assessments of the 24 tools by two assessors yielded an average agreement rate of 90.5% across 10 criteria, with straightforward criteria (e.g. C1, C2, C4) achieving 100% agreement. Divergences are primarily due to a certain degree of lack of precise delineation in the 5-point scoring scale, as well as differences in information sets used during the independent assessment. The lowest agreement rate (67%) was observed for C5 Class, attributed to the inherent complexity of tools addressing multiple functional classes. Following refinements to the criteria definitions and evaluation methods, a second round of assessment achieved 100% consistency in ratings between the two assessors, this assessment result was used for further analysis (appendix 4).

2.3. Limitations

While this study aimed at providing a comprehensive overview of biomimetic tools, several limitations should be noted. (1) The assessment focused on biomimetic tools that are currently accessible and meet the defined criteria, and there may be other tools that were not included due to limited information or restricted accessibility. (2) The criteria were carefully defined, however, due to time and resource constraints some criteria could not be included, e.g. criteria to test user-friendliness and -acceptance, outcome fidelity, breadth of applicability to different scenarios, or whether the tools incorporated sustainability. The self-sufficiency index was used to establish a link to user-experience-related research; however, this is only a starting point. Criteria linked to empirical applications are also lacking due to limited retrievable information regarding the selected 24 tools. Broader empirical analyses, including user research, and conducting interviews with both academic and industry stakeholders, can be a future

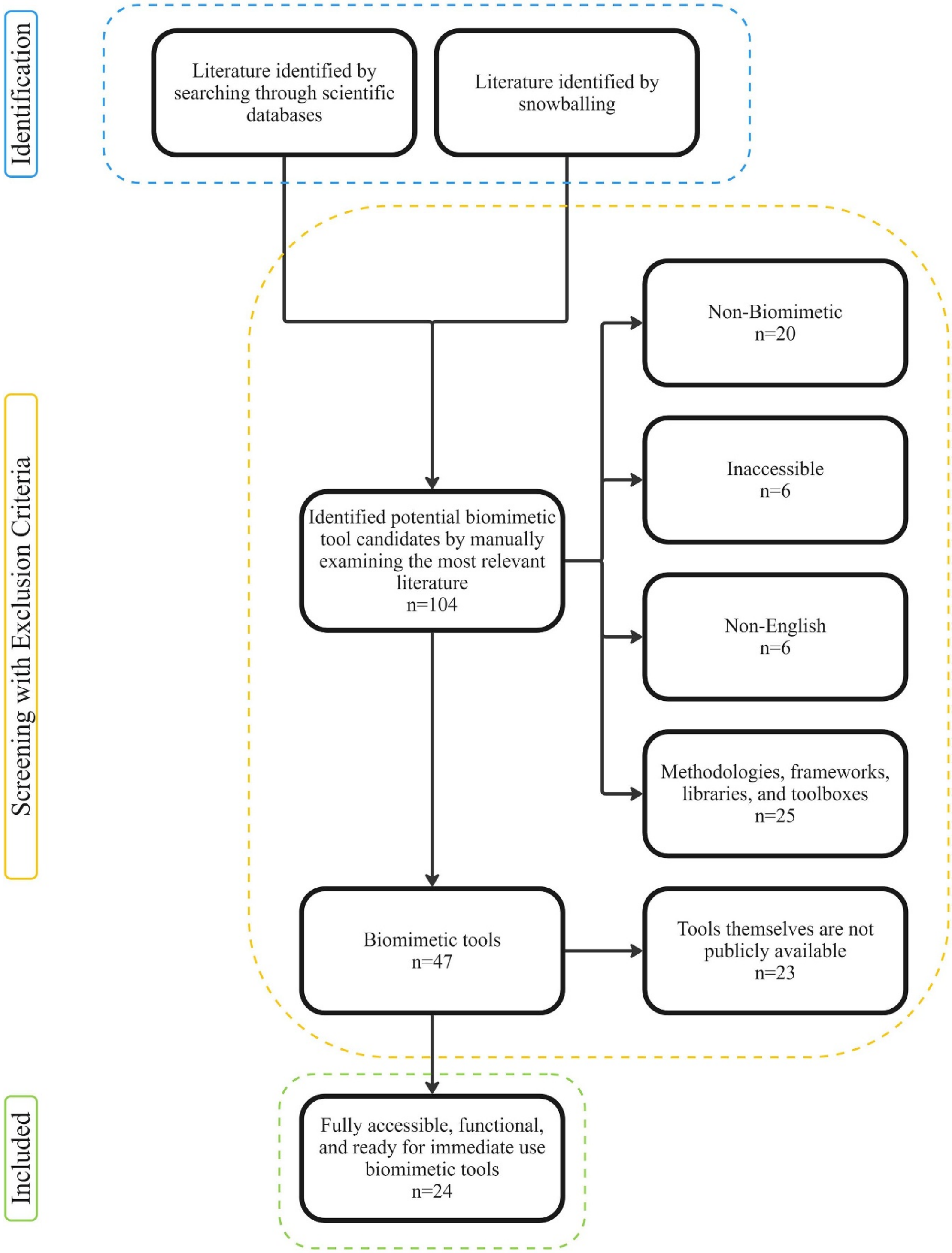

Figure 1. The biomimetic tool identification and classification scheme was adapted based on the PRISMA diagram. 'n' refers to the number of items in each category. Initially, the identification methodology marked in blue resulted in 104 identified items with the potential to meet the study's scope. Then, the screening process stated the exclusion criteria on the right-hand side in yellow resulting in the determination of 24 included tools in green. 'Non-Biomimetic n = 20' are items that have been mentioned in biomimetic-related literature but are not created with the intention of biomimetics; 'Inaccessible n = 6' are items that are not accessible due to the lack of retrievable information online; 'Non-English n = 6' are items that are accessible but do not provide an English version; 'Methodologies, frameworks, libraries, and toolboxes n = 25' are items that support the biomimetic process but do not fit this study's definition of a biomimetic tool; 'Tools themselves are not publicly available n = 23' are items fitting the biomimetic tool's definition, and have relevant available information describing the tools (e.g. published research papers) but do not provide access to the actual tools at the time of this research.

research direction. (3) Although the assessment criteria were clearly defined, some degree of subjectivity is inherent in the process of this study, particularly in areas requiring the assessors' judgment; however, steps were taken to mitigate bias, such as involving multiple authors with diverse expertise and establishing detailed evaluation methods, which are described in the supplementary material (appendix 1).

Table 2. Overview of the 10 established criteria. With code, name, explanation, and a concise version of the evaluation method. Continued on the next page.

Code	Name	Explanation	Evaluation method (concise version)
C1	Year of release	Indicates the year the tool was first released, reflecting its current relevance and development history.	**Year**
C2	Accessibility	Assesses the tool's accessibility by evaluating its open-source status, cost structure, and format availability, to determine user access ease.	**Open-source status** Yes; No; NA **Cost structure** Full free access; free with registration; paid access **Format availability** Interactive online platform; standalone algorithm; static document format
C3	Stage of development	Categorizes the tool based on its development status, from the testing phase to well-proven applications, indicating its maturity and reliability. 'External' in this criterion means the tool is shared with people outside the development team.	**Scale 1–4:** 1 Limited external testing 2 Open external testing 3 Official release 4 Well-proven
C4	Approach	Classifies the tool based on whether it supports solution-based, problem-driven, or both approaches in biomimetic processes.	**Approach 1, 2, 3:** 1 Solution-based 2 Problem-driven 3 Both
C5	Class	Categorizes tools based on their function in the biomimetic process, including problem analysis, problem abstraction, biological analysis, biological abstraction, technical specification, transfer, implementation, and assessment.	**Class 1–8:** 1 Problem analysis 2 Problem abstraction 3 Biological analysis 4 Biological abstraction 5 Technical specification 6 Transfer 7 Implementation 8 Assessment
C6	Type	Classifies tools based on their core functions, including interactive data platforms, catalogues, computational and algorithmic tools, inspiration card decks, structured workflow templates, and process facilitation tools. This helps to understand each tool's primary utility and application within biomimetics.	**Type 1–6:** 1 Integrated data platforms 2 Catalogues 3 Computational and algorithmic tools 4 Inspiration card decks 5 Structured workflow templates 6 Process facilitation tools
C7	Biological strategies coverage	Indicates the extent to which a tool incorporates and facilitates the application of biodiversity and ecological knowledge in the biomimetic process by assessing the number of biological strategies covered. A biological strategy is defined as a combination of a biological organism or system and a function. The assessment scale is non-linear to cover the wide range of strategies provided by different tools.	**Scale 1–5:** 1 <20 biological strategies 2 20–100 biological strategies 3 100–1000 biological strategies 4 1000–5000 biological strategies 5 >5000 biological strategies

C8	Scientific foundation	Evaluates the accuracy, reliability, and originality of the scientific information provided by the tool.	**Scale 1–5:** 1 Lacks originality and reliability 2 Minimal originality and questionable reliability 3 Moderate originality and reliability 4 High originality and reliability 5 Exceptional originality, reliability, and currentness
C9	Self-sufficiency information index	Assesses whether a tool provides enough detailed information for users to independently learn and utilize it effectively, thus impacting the ease of the learning process and overall usability.	**Scale 1–5:** 1 Minimal information 2 Basic information 3 Moderate information 4 Comprehensive information 5 Extensive and detailed information
C10	Reproducibility	Assesses the tool's capability to produce consistent outcomes by different users within the same time period, thereby indicating its reliability and robustness.	**Scale 1–5:** 1 Highly variable 2 Moderately variable 3 Moderately consistent 4 Consistent 5 Highly consistent

3. Results and discussion

3.1. Tool identification result

Based on the previously described methodology, 24 biomimetic tools were identified as fully accessible, functional and ready to use. Table 3 gives an overview of these 24 tools including their codes, names, descriptions, and references. For more details such as release years or links to the tools, see appendix 3.

A comparison with Wanieck *et al* (2017) further emphasises the evolving nature of biomimetic tool development. Seven of the tools (BT-01, BT-08, BT-12, BT-13, BT-15, BT-17, BT-18) from the current study's 24-tool list overlap with the 43 tools identified in the study by Wanieck *et al* (2017). 13 tools from the current list were introduced after Wanieck *et al* (2017) published their study. Many of the tools from Wanieck *et al*'s (2017) list no longer meet the criteria for readily accessible and usable tools. However, the seven overlapping tools have withstood the test of time, offering insights into how tools can remain relevant. For example, AskNature's (BT-01) continuous updates and maintenance, as well as the robustness and foundational nature of the E2B-Thesaurus (BT-17), contribute to their ongoing usability. The emergence of numerous new tools also reflects positive development in the field, indicating a continuous development of biomimetic tools. Notably, while the affiliation of the tools did not play a role in the tool screening process (figure 1), 6 of the 24 tools (BT-01, BT-11, BT-12, BT-13, BT-14, BT-24) are affiliated with the sister organizations The Biomimicry Institute & Biomimicry 3.8, which may offer insights into strategies for enhancing public visibility and ensuring ongoing relevance in future development.

3.2. Tool assessment results

This section will analyse the findings from the tool assessment results, drawing connections across various criteria to highlight broader trends, implications, and gaps. The aim is to provide a holistic view of the biomimetic tools' landscape, identifying overarching themes and discussing the practical significance of the assessment results. To optimise clarity and brevity, overlapping criteria are grouped for analysis, rather than presented in strict numerical sequence. This approach enables a focused discussion of the most critical findings while comprehensively addressing the assessment outcomes of all 10 criteria.

3.2.1. Integration of year of release, accessibility, and types

Figure 2 illustrates the distribution of release years (C1) for the 24 assessed tools, categorized by typology (C6). The release years span the period from 2006 to 2024, covering 19 yrs. The highest number of tool releases occurred in 2015 and 2020, with three tools released in each year. Overall, there has been a consistent release of on average 1.3 new tools each year. The assessment was done based on the currently available version of the tools, while C1 refers to the release year of the tool's original version, thus upgrades are not included as new releases and are not reflected in figure 2.

Table 3. Overview of the 24 fully accessible, functional, and ready for immediate use tools in alphabetical order. Continued on the next pages. BT: Biomimetic Tool.

Code	Name	Description	References
BT-01	AskNature	AskNature is a website that provides access to more than 1700 strategies and solutions to inspire innovative designs, offering a database of nature-inspired ideas and case studies for various applications. (https://asknature.org/)	Deldin and Schuknecht (2013)
BT-02	BARcode	BARcode is a search engine designed to facilitate the retrieval of biomimetic information integrating semantic technologies and data programming to enhance the precision and relevance of search results. (https://github.com/emunatool/BARcode-BioInspired-Search)	Emuna *et al* (2024)
BT-03	BIDARA	BIDARA is an AI-driven (ChatGPT by OpenAI) tool developed by NASA to facilitate biomimetic research, enabling users to explore and apply biological strategies through an interactive chatbot interface. It integrates the Biomimicry Institute's design methodology to support sustainable design solutions by mimicking nature's principles. (https://github.com/nasa-petal/bidara)	Nasa-Petal (2023)
BT-04	BioCards	BioCards is a card-fabrication tool used in bio-inspired design to document biological phenomena and their functional principles, aiding in ideation by providing structured analogical reasoning to generate innovative solutions.	Lenau *et al* (2015)
BT-05	BioId support	BioId support is a tool designed to enhance collaboration between engineers and biologists by facilitating the transfer of biological analogies into technical solutions, aiming to improve the quality and innovative potential of bio-inspired design ideas. It combines aspects from BioCards (BT-04) and KoMBi (BT-19) tools supporting the participants to use sketching and graph representation.	Farzaneh (2020)
BT-06	BID Canvas	Bio-inspired design (BID) Canvas, based on Concept-Knowledge (C-K) Theory, provides a template with guidelines for creating innovative, nature-inspired concepts, enhancing knowledge transfer, and fostering connections between biology and engineering. (https://jacquelynnagel.com/bid-canvas/)	Nagel *et al* (2017)
BT-07	Bioinspire-explore	Bioinspire-explore is a website designed for taxonomy-driven exploration of biodiversity data, facilitating bioinspired innovation by providing practical examples, visualizations of species' relationships, habitats, and links to other information sources. (https://bioinspire-explore.mnhn.fr/)	Saint-Sardos *et al* (2024)
BT-08	Biologically meaningful keywords	Biologically meaningful keywords tool systematically translates functional engineering terms into biologically meaningful keywords to facilitate finding relevant biological analogies for engineering design problems, thereby assisting the biomimetic design process.	Cheong *et al* (2011)
BT-09	BiOMIg search*	BiOMIg Search is a website with a search engine that applies AI to identify biological models within a specialized database of 4 million scientific publications, facilitating the retrieval and comprehension of relevant biological data for biomimetic applications. (https://biomig-search.com/) *As of January 2025, BiOMIg Search was integrated into Asteria - a new professional software for biomimicry, for more information please address platform Asteria. (https://www.asteria.life/)	Tchakarov *et al* (2023)

(Continued.)

Table 3. (Continued.)

BT-10	Biomimicards	Biomimicards is an educational card game that teaches biomimicry through 24 nature-inspired challenges, encouraging players to use creativity and collaboration. (https://biomimicards.com/)	Circulab (2018)
BT-11	Biomimicry 3.8 cards	Biomimicry 3.8 cards are an educational tool designed to teach biomimicry concepts through card sets, where users learn about various biological strategies and their potential applications in both societal and technical contexts.	Biomimicry 3.8 (2016)
BT-12	Biomimicry DesignLens (Life's principles)	Biomimicry DesignLens tool offers guiding principles for applying biomimicry principles to design, helping users integrate nature's strategies into their projects through a guided, non-linear methodology.	Biomimicry 3.8 (2023)
BT-13	Biomimicry Taxonomy	Biomimicry Taxonomy tool categorizes biological strategies by function, streamlining the search for nature-inspired solutions tailored to specific challenges. It offers search queries for AskNature (BT-01) and facilitates biological knowledge transfer. (https://asknature.org/resource/biomimicry-taxonomy/)	Biomimicry Taxonomy (2008)
BT-14	Biomole	The Biomole tool is an interactive visualization website that facilitates bio-inspired design by allowing users to explore and search AskNature (BT-01) dataset through functional co-occurrence, aiding in the identification and application of biological strategies to engineering problems. (http://biomole.asknature.org/)	Eggermont *et al* (2019)
BT-15	BioTRIZ	BioTRIZ is a tool that integrates the principles of the TRIZ problem-solving framework with biological strategies to offer systematic innovation solutions by drawing analogies from natural systems.	Vincent *et al* (2006)
BT-16	E2BMO	E2BMO is a tool that facilitates the translation of engineering problems into biological solutions by using an engineering-to-biology thesaurus and ontology, aiding in the development of innovative bio-inspired designs. (www.uakron.edu/bric/E2BMO/index.html)	McInerney *et al* (2018)
BT-17	E2B-thesaurus	E2B-thesaurus is a tool that facilitates the translation of biological concepts into engineering terms to promote collaboration between biologists and engineers and aid in the creation of biologically inspired engineering solutions.	Nagel *et al* (2010)
BT-18	Four-box method & T-chart	Four-box method: This tool supports the tasks of problem formulation in biologically inspired design by organizing the problem into four categories: function, operational environment, specifications/constraints, and performance criteria. T-Chart: This tool facilitates the comparison of a design problem and a biological analogy by mapping each element of the problem to the corresponding element of the analogy, aiding in the evaluation of the analogy's relevance and applicability to the design problem. Four-Box Method & T-Chart complement each other and are therefore treated as one tool in this study.	Helms and Goel (2014)

(Continued.)

Table 3. (Continued.)

Code	Name	Description	References
BT-19	KoMBi	KoMBi is a tool that focuses on integrating aspects from both biology-specific and engineering-specific models into a unified modeling approach, utilizing visual representations to bridge communication gaps and support collaborative innovation in technical product development.	Hashemi Farzaneh *et al* (2015)
BT-20	LINKAGE	LINKAGE tool is a website designed to enhance interdisciplinary communication and efficiency in biomimetic design by providing a common scheme for both biologists and engineers, supporting the information gathering, structuring, and abstraction processes necessary for modeling technical problems and biological solutions. (https://linkage-lcpi.com/)	Graeff *et al* (2021b)
BT-21	MIMICUS basic data cloud platform	MIMICUS basic data cloud platform is a website designed to facilitate the search for biological models and eco-friendly product development ideas, offering access to a vast database of biomimetic design cases and background knowledge. (www.mimic.us/)	MIMICUS Basic Data Cloud Platform (2021)
BT-22	MIMICUS public library	MIMICUS public library is a website offering a collection of biomimicry-related publications, patents and research materials, aimed at supporting and advancing the study and application of nature-inspired solutions. (www.lib.mimic.us/)	Nature-based Solutions Public Library by MIMICUS (2022)
BT-23	Morphino	Morphino is a card-based tool designed to inspire the creation of shape-changing interfaces by providing examples of morphing mechanisms found in nature, aimed at fostering interdisciplinary collaboration in human-computer interaction (HCI), material science, and robotics. (https://usabilitypanda.com/morphino)	Qamar *et al* (2020)
BT-24	Nature's unifying patterns	Nature's unifying patterns is a tool that identifies overarching lessons from the natural world, emphasizing ten key principles that guide biomimetic design to ensure compatibility with life on Earth.	Nature's Unifying Patterns—Biomimicry Toolbox (2015)

An examination of the typology over time shows a notable development from an initial predominance of catalogues during the early years (2006–2011) to a subsequent prevalence of structured workflow templates (2013–2016) and finally, a pronounced increase in integrated data platforms featuring AI functionalities after 2021. This trend towards integrated data platforms in the 2020s indicates a growing interest and technological advancements in this area. In two cases, tools were based on previously existing tools: E2B-Thesaurus (BT-17) was published in 2010, followed by the development of E2BMO (BT-16) in 2018 (Nagel *et al* 2010, McInerney *et al* 2018). Similarly, BioID Support (BT-05) (Farzaneh 2020), which appeared in 2020, is related to the KoMBi approach (BT-19) (Hashemi Farzaneh *et al* 2015) and BioCards (BT-04) (Lenau *et al* 2015), both of which were published in 2015. It can be observed that when newer tools are developed based on older tools, they tend to retain the same type as their predecessors. For instance, the digitization of E2B-Thesaurus to E2BMO did not cause a typology change as the core function remained a catalogue.

The generally observed typology development trend from the catalogue of data to integrated data platforms indicates a clear technological transition that can be directly linked to the integration of technological innovation in tool development. These new digital tools are not officially built on pre-existing biomimetic tools, but they generally use common concepts and frequently make use of existing databases such as OpenAlex, Asknature, Global Biodiversity Information Facility, etc. (Tchakarov *et al* 2023). The development of computational tools was considered a requirement for the transformation of biomimetics into a scalable and repeatable methodology (Goel *et al*

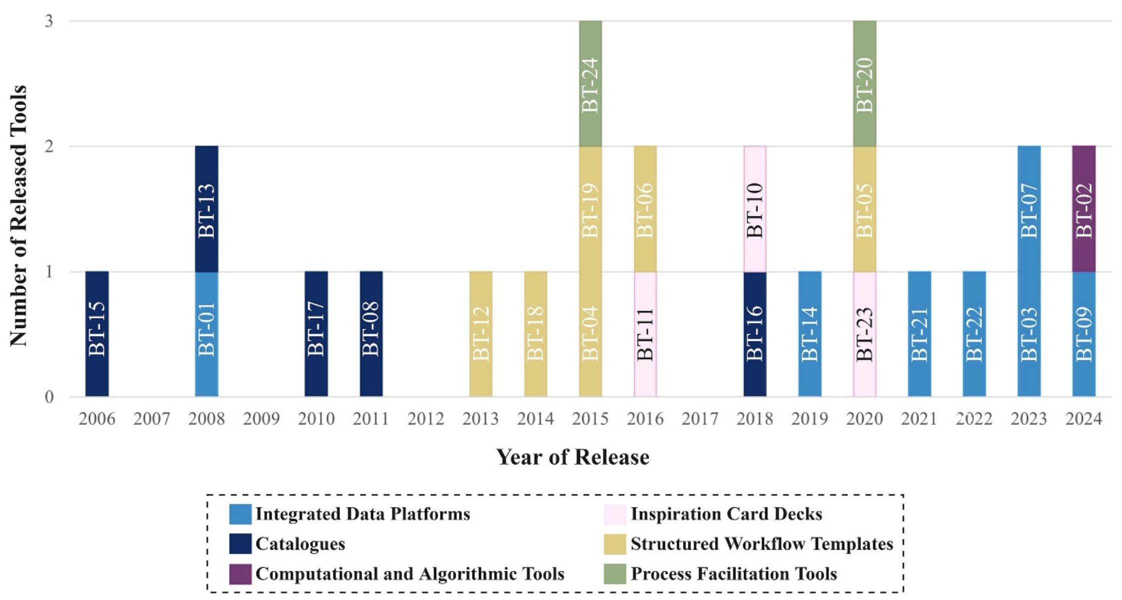

Figure 2. Typology trends in biomimetic tool development (2006–2024).

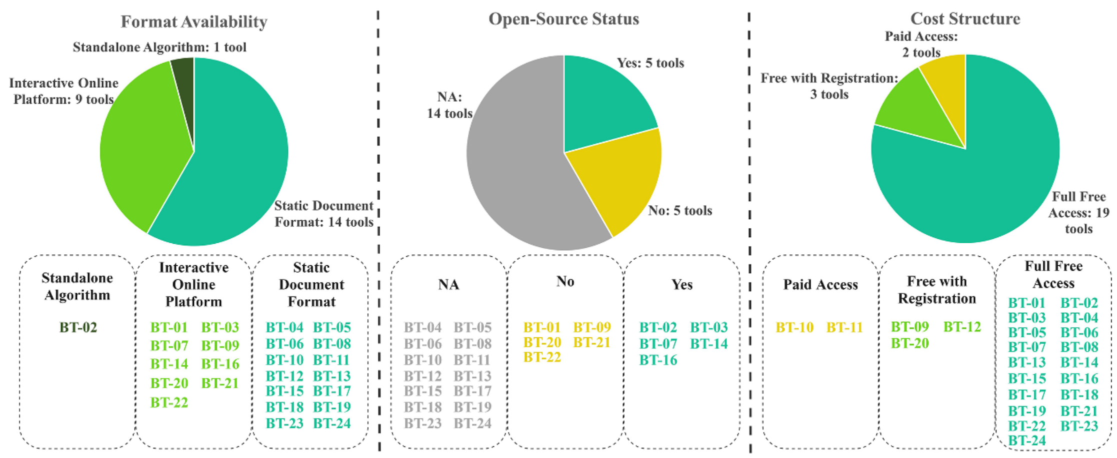

Figure 3. Accessibility (C2) results overview. This criterion consists of 3 individual sub-criteria.

2014). Two tools are process facilitation tools, namely LINKAGE (BT-20) and Nature's Unifying Patterns (BT-24), that are designed to streamline and enhance particular steps within the biomimetic development process.

A further indication of the impact of digitisation is provided by accessibility (C2), which assesses the open-source status, cost structure, and format availability of a tool (figure 3). When combining the accessibility (C2) with the year of release (C1), the format availability indicates a notable switch from predominantly static document formats- typically lacking automation and requiring manual operation by the user- up until 2020 to one standalone algorithm (BT-02) and otherwise exclusively interactive online platforms since. These platforms often feature high levels of automation, good interactivity, ease of maintenance, and upgradeability, making them more accessible. Among the 11 tools with a source code, 6 have an open-source status and 5 did not disclose their code, showing a close to even distribution without a clear trend in time (figure 3). Only BARcode (BT-02) is classified as a 'Standalone Algorithm' format, and it is open-source. This limited number is likely due to many algorithm-based projects remaining at the experimental stage in laboratories or being developed into interactive online platforms.

'Format Availability' simply refers to the form in which the tool exists, when combining this information with 'C6 Type' that highlights the tool's primary function, they provide a more in-depth understanding of the tool's characteristics. For instance, while format availability and tool type typically align as expected, E2BMO stands out as the only catalogue-type tool available in an interactive online platform format, making it the most accessible and interactive among catalogue tools in this study. By distinguishing

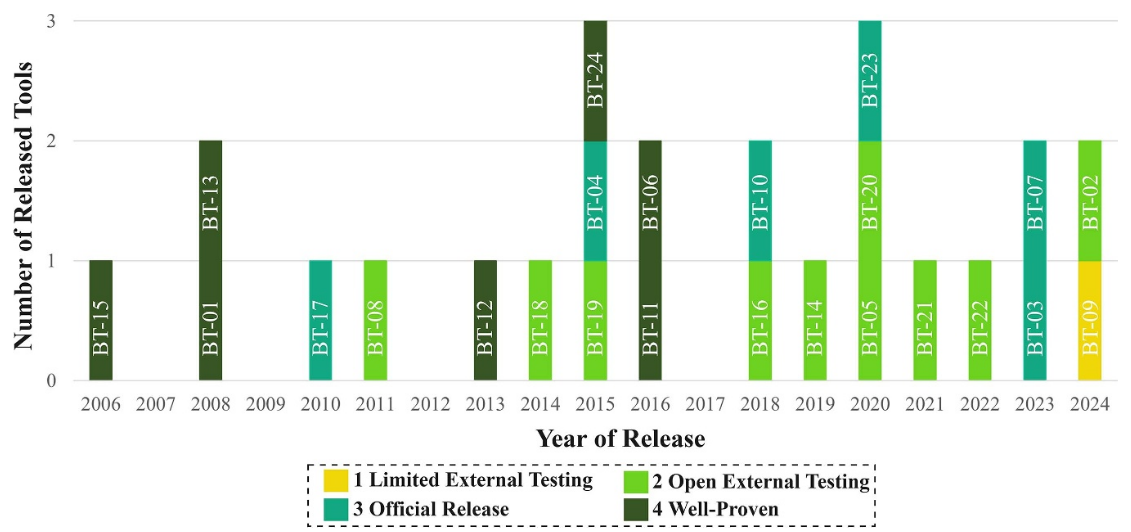

Figure 4. Stage of development (C3) combined with year of release (C1). 1- Limited external testing: 1 tool; 2- open external testing: 10 tools; 3- official release: 6 tools; 4- well-proven: 7 tools.

between function type and format, each criterion more accurately reflects a specific aspect of the tool.

Only two tools require payment, both of which are card-based tools (BT-10 Biomimicards and BT-11 Biomimicry 3.8 cards). Three tools (BT-09 BiOMIg Search, BT-20 LINKAGE and BT-12 Biomimicry DesignLens) are free but require the user to register (Graeff *et al* 2021b, Biomimicry 3.8 2023, BiOMIg Search 2024). BiOMIg Search is marked with an asterisk in the file (see appendix 4) as it is still in the alpha testing stage, with the final cost structure unknown for its official release. Additionally, it is important to note that BIDARA (BT-03) is based on ChatGPT by OpenAI, requiring users to register for ChatGPT and pay the corresponding fees (Nasa-Petal 2023). Here, it is marked as 'Full Free Access' because BIDARA itself does not collect user registration information or charge fees. Tools that exist in the publicly published scientific literature are classified as 'Full Free Access', although authors are aware that accessing certain literature itself may require a subscription or purchase.

Of the 24 tools evaluated, 22 do not require financial investment, which indicates a general tendency within the field to make tools freely accessible to users, reflecting a collaborative and supportive environment. Most tools (n = 19) are products of scientific research or funded by non-profit organizations, explaining their free availability (Emuna *et al* 2024, Saint-Sardos *et al* 2024).

3.2.2. Tool maturity and accessibility in time

Figure 4 illustrates the stage of development (C3) of the tools in combination with their release years. As expected, older tools are generally further developed and proven than more recent tools. A connection between the stage of development and certain tool types could not be established.

BiOMIg Search (BT-09) is the only tool that falls into the category of '1 (Limited External Testing)', given that it was accessed using an alpha test account during the research period (BiOMIg Search 2024). It was included in the study due to the responsiveness of the BiOMIg Search developer team, who promptly granted access to the tool upon request. Most tools (42%) are rated as '2 (Open External Testing)' suggesting active community engagement and iterative improvement. This rating applies to tools that are fully accessible and functional yet described as being in the testing phase/prototype stage, having future development goals, or lacking a formal release declaration. Notably, 67% of the assessed tools were rated '2' or '3 (Official Release)', which means they are publicly available without sufficient evidence of their abilities validated in empirical cases. As seen in figure 4, this is only partially time-dependent, considering tools that have been developed for more than 5 years have not been publicly well-proven to the authors' knowledge. Plausible reasons for this include: (1) Tools published in scientific literature mainly circulate within the research community. Subsequent studies tend to reference or adopt parts of these tools' principles without conducting empirical validation research on the tools themselves, as observed in the BioID Support (BT-05) (Farzaneh 2020). (2) Some tools cease development after public testing, lacking further follow-up and hence not undergoing additional development. Some examples include the Four-Box Method & T-Chart (BT-18) (Helms and Goel 2014) and the MIMICUS Public Library (BT-22) (Nature-based Solutions Public Library by MIMICUS 2022). (3) The application scenarios for these tools may involve educational use in schools, or real-world product development within the industry fields. In such cases, the tools may be used and validated without disclosing the cases in publications, such

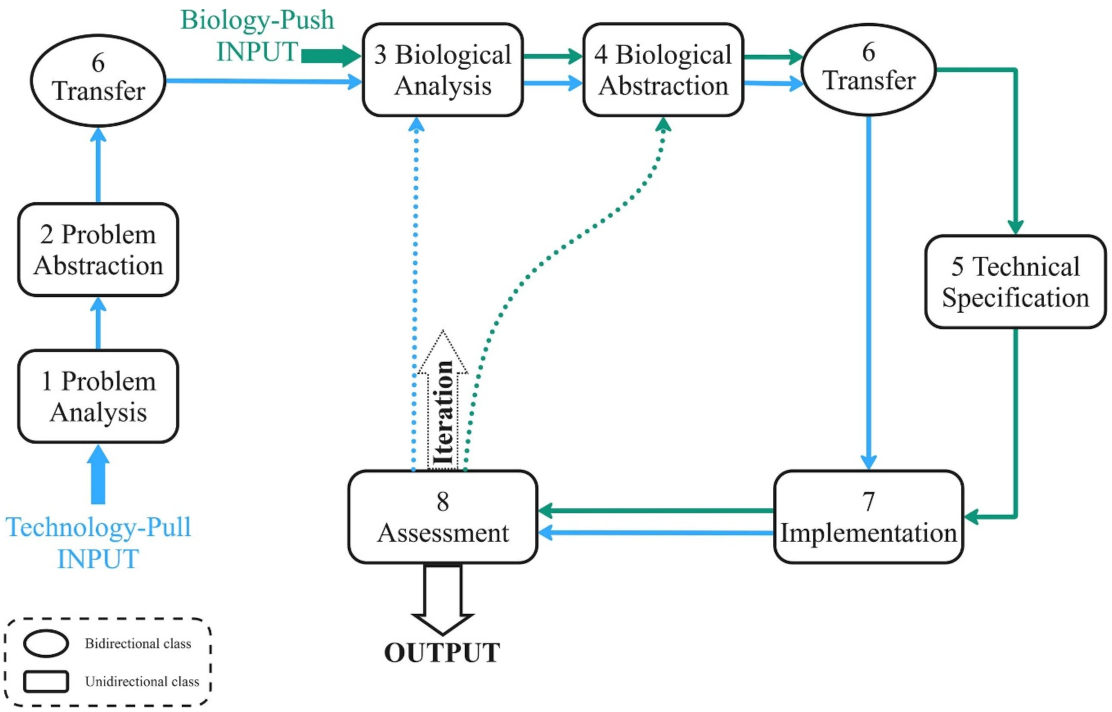

Figure 5. Class (C5) - the established eight classes and their sequence in a combined flowchart for biology-push and technology-pull biomimetic processes. The biology-push (or bottom-up/solution-based) approach is indicated with green arrows, and the technology-pull (or top–down/problem-driven) approach is indicated with blue arrows. Class 6 transfer appears twice in this figure as the only bidirectional class in the process: illustrating the knowledge shift from engineering to biology on the left side and from biology to engineering on the right side. Although transfer tools are inherently bidirectional, their application direction is determined by the stage of process in biology-push/technology-pull.

as the case with the tool LINKAGE (BT-20) (Graeff *et al* 2021b).

In practical use, tools rated '2' and '3' show no significant difference in delivering their designed function. Identifying tools in the early stages of development can provide opportunities for researchers and developers to collaborate and improve these tools, fostering their growth and maturity. Seven tools (29%) are rated '4 (Well-Proven)', meeting the criteria of having been validated through practical applications. This includes commercial projects, educational settings, or focus group tests, demonstrating the tools' functionality and effectiveness. For instance, BioTRIZ (BT-15) has documented case studies such as 'Green product design based on the BioTRIZ Multi-Contradiction Resolution Method' (Bai *et al* 2020), and Nature's Unifying Patterns (BT-24) includes concrete application cases used in biomimetic education and knowledge dissemination (Ohlander *et al* 2018, Aboulnaga and Helmy 2022).

3.2.3. Tool class overview

Based on previous research, this study established the 8-class criterion for the biomimetic process, incorporating frameworks such as the unified problem-driven process of biomimetics (Fayemi *et al* 2017), the biology push and technology pull approaches from VDI (VDI 6220 Part 1 2021, VDI 6220 Part 2 2023), and the Design Spiral proposed by the Biomimicry Institute (Biomimicry Institute 2017). These frameworks share common elements, which were considered in developing the 8 classes for this criterion. The order of these classes in the biomimetic process is detailed in figure 5.

Figure 5 illustrates the sequence of both the biology-push and technology-pull approaches within a single diagram, clearly demonstrating the sequential relationships between the different classes and highlighting the correlation between the two approaches. The biology-push process begins with Biological Analysis- in which a biological model (organism or system) with its strategy is described, and Biological Abstraction- where the core function of this model is abstracted to a general concept that can be later transferred to technology. Then after the Transfer class (knowledge transfer from biological to technical), the process goes through Technical Specification where technical aspects of the principle are detailed (e.g. material characteristics, dimensions, application environment) before reaching the Assessment. This Assessment class is a novel class created based on this study's evaluation needs, tools support this class enable an overall evaluation of a biomimetic project and its outcomes upon completion, allowing for reflection on the project's success, areas for improvement, and lessons learned. If the assessment results do not meet the project requirements, the process will follow the dashed arrow back to

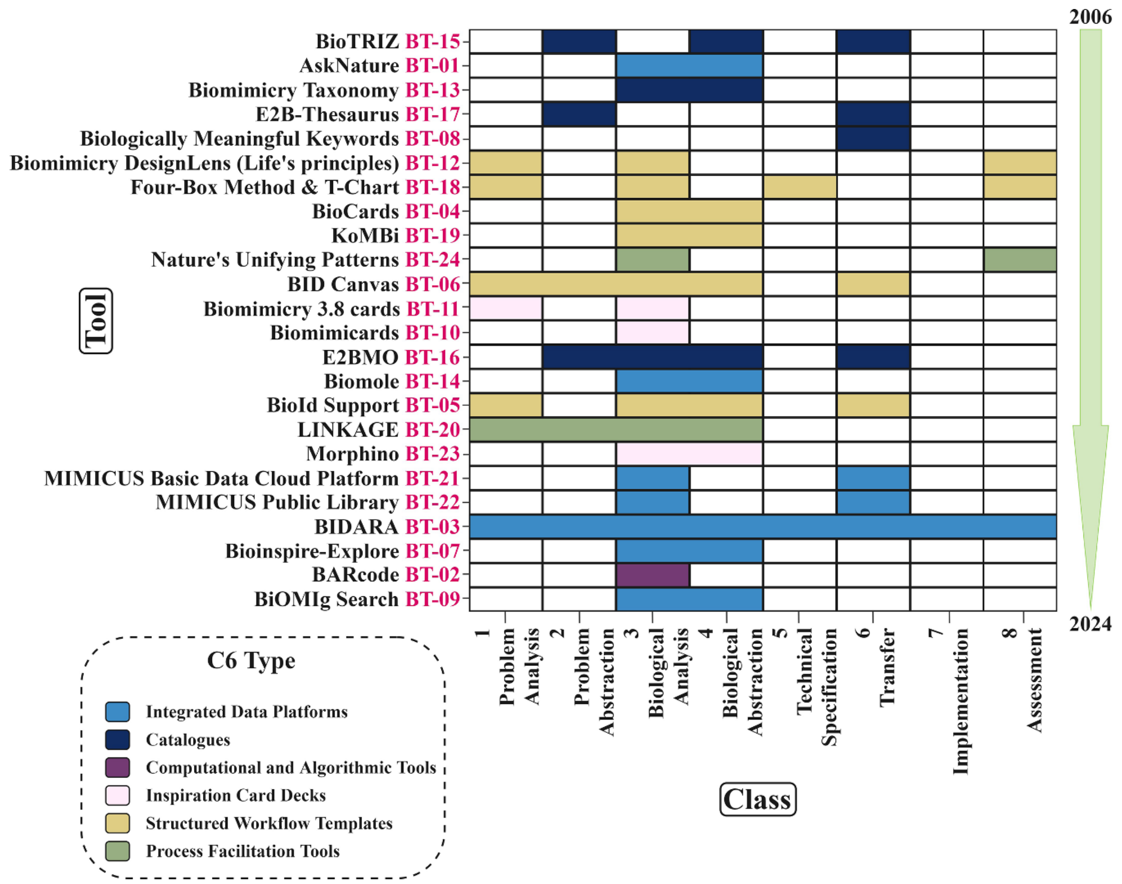

Figure 6. The assessment results of class (C5) combined with type (C6) in chronological order of release years (C1). The blocks show the corresponding tools' classes. The six types are color-coded as stated in the legend (C6 Type). The arrow on the right-hand side indicates the tool release timeline, from 2006 to 2024.

Biological Abstraction for further iterations until satisfactory outcomes are achieved. The technology-pull approach starts with Problem Analysis- in which a technical or societal problem is analyzed and defined, and Problem Abstraction- where the problem is generalized to a transferable technical problem description. Then after the problem is transferred to the biological side, the process passes through 4 other intermediate stages overlapping with the biology-push process before reaching the Assessment potentially followed by further iterations. There are two major differences compared to the unified problem-driven approach (Fayemi *et al* 2017): (1) After the assessment class, the starting class for a new iteration differs between the two approaches. In technology-pull, there is usually no need to reanalyze the technical problem (this builds on the basis that the initial problem analysis is sufficient and thorough); instead, reselecting a biological model is an important strategy for improving the outcome. In biology-push, the biological model is typically fixed, so iteration begins with rethinking the abstraction of the biological model. (2) In the two approaches, problem analysis and abstraction apply exclusively to the technology-pull approach, while technical specification is designated for the biology-push approach. When a project follows the biology-push route, the absence of a predefined technological problem or application scenario means that, even after abstracting and transferring biological knowledge, the concrete implementation path remains ambiguous. Hence, before moving on to practical implementation, a technical specification class was established. This involves using relevant tools to analyze the technological capacity of the adapted biological insights—such as identifying materials, dimensions, and viable application environments—to establish a foundation for subsequent implementation. By contrast, the technology-pull approach typically begins with a well-defined problem, allowing immediate prototyping or testing once the biological principles have been abstracted and transferred. The addition of technical specification to the biology-push workflow ensures that the resulting solution is firmly rooted in real-world conditions and is more readily adaptable for market or technological development.

Each of the 24 tools was evaluated by the two assessors according to these classes, with the results shown in figure 6. For this criterion, the eight classes are not mutually exclusive- a single tool may correspond to one or multiple classes.

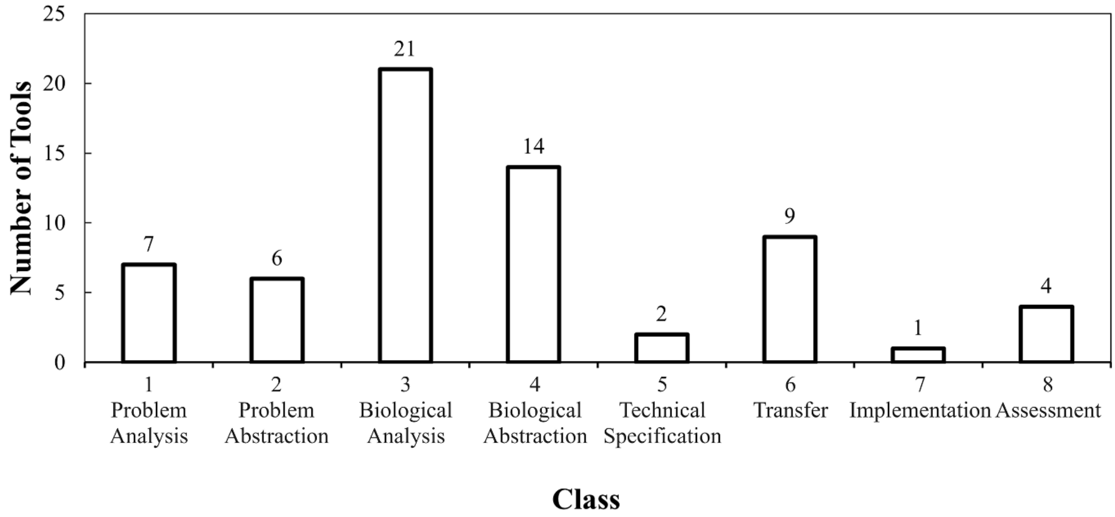

Figure 7. An overview of the number of tools across eight classes (C5).

Some tools are limited to a single class, such as Biomimicards (BT-10) (Circulab 2018) for 3-Biological Analysis and Biologically Meaningful Keywords (BT-08) (Cheong *et al* 2011) for 6-Transfer, indicating their specific function in a particular stage of the biomimetic process. Other tools, like BIDARA (BT-03) (Nasa-Petal 2023), support all eight classes due to its foundation on OpenAI's ChatGPT, which inherently possesses extensive capabilities. BID Canvas (BT-06) (Nagel *et al* 2017), a static document, supports five classes due to its instructive and flexible design. The average of classes covered does not differ greatly between different types as the variation within each tool type is high. Still, card-based tools can be found covering fewer classes on average, and structured workflow templates at the higher end cover on average more than three classes. This evaluation only assesses the applicable classes for each tool without judging their quality, as the higher number of classes a tool covers does not imply superiority. Figure 6 can aid practitioners in identifying suitable tools based on their current stage in the biomimetic process.

The chart in figure 7 summarizes the number of tools available for each class, showing a clear concentration of tools in classes 3 and 4, which are biological analysis and abstraction tools. The analysis of this chart revealed several insights: (1) Tools for biological classes (classes 3 and 4) significantly outnumber those for technical classes (classes 1, 2 and 5). The highest number of tools for biological analysis class provides researchers with resources for searching and identifying biological models. As for the three classes connected to the technical side, problem analysis and abstraction can be supported by various other tools from different fields, such as brainstorming and innovative thinking, which are beyond the scope of this study. There are only two tools for technical specification, which presents an opportunity for developers to create new tools supporting this critical class of the biomimetic process. Ensuring a balanced approach by incorporating tools from both technical and biological sides could lead to more comprehensive and effective biomimetic solutions. (2) The most significant gap shown in the chart is in class 7- Implementation, supported by only one tool. However, the authors do not consider this a true gap in the tool development field. Given the nature of this study, which focuses solely on tools within the biomimetics domain, implementation is indeed a crucial phase of biomimetics but is not lacking in tools. On the contrary, this phase can utilize a multitude of tools from other fields, such as various prototyping tools, mockup software, CAD, etc. (3) In this study, a new class 8- Assessment has been added to the process flow. This class is less emphasized in other frameworks, and of the 24 tools evaluated in this research, 4 support this class (BT-03, BT-12, BT-18, BT-24). The value of this class extends beyond ensuring the quality of the current project, when it also holds the potential to positively influence future projects. This underscores the importance of having a platform that facilitates the sharing of assessment reports. Despite the numerous ongoing biomimetic projects in both academic and industrial fields, the best-known examples of successful biomimetic applications remain those like VELCRO® (Velcro IP Holdings LLC 2024), the lotus effect self-cleaning paint (Lotus-Effect® 2024), or the gecko tape (Geim *et al* 2003), etc. While academic research often publishes research papers, the industry rarely shares its insights and experiences. If practitioners in the field can more openly present project assessment reports and share lessons learned,

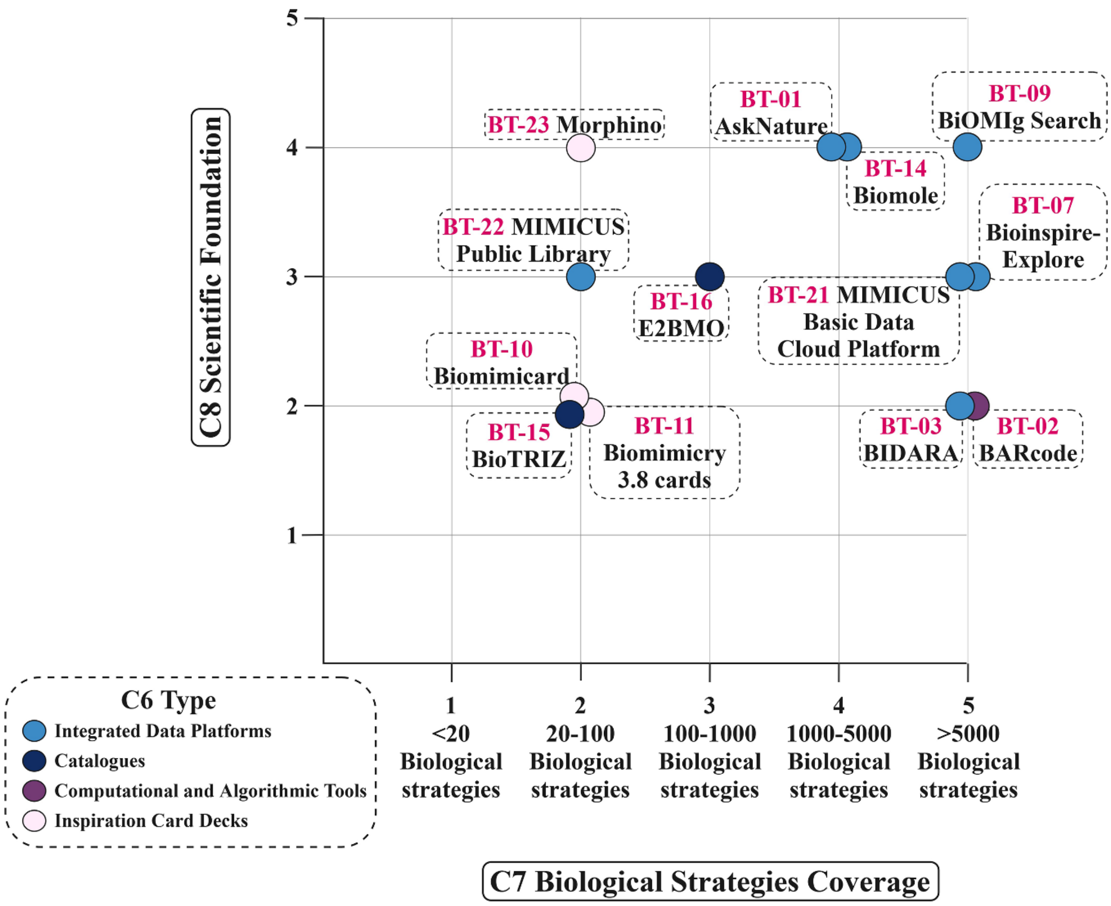

Figure 8. Integrated overview of biological strategies coverage (C7), scientific foundation (C8), and type (C6). Structured workflow templates and process facilitation tools do not provide specific biological strategies and are therefore not shown in this figure. Note that all scores are integers- overlapping circles in the figure indicate that multiple tools share the same score for the two criteria, occupying the same coordinate point.

it could significantly advance the entire biomimetic field.

3.2.4. Quality and quantity of biological information across various tool types

To indicate the range of biodiversity a tool provides, C7 reflects the quantity of biological strategies, and it is directly linked and supported by C8 Scientific Foundation, a qualitative criterion. Linking C7 and C8 outcomes allows for comparing the quantity and quality of biological information across various tool types. As mentioned in the methodology chapter, criteria such as C7 and C8 only apply to tools that provide biological strategies, other tools are evaluated as 'NA' and thus not shown in figure 8.

Card-based tools provide the lowest number of biological strategies ranging between 20 to 100. This is likely due to the constraints of a physical card set, which by design has a limitation: Covering a range of 20–100 strategies is reasonable while attempting to cover thousands of strategies would be impractical in terms of both production effort and user experience. There are however differences in the quality of scientific information the card decks provide, with Morphino (BT-23) reaching a high score as it includes detailed biological information and references to the information sources. This difference aligns with their respective design intentions: Morphino illustrates established morphing mechanisms through biological examples to inspire shape-changing interface designs within HCI community (Qamar *et al* 2020), whereas the other two (BT-10 and BT-11) are designed as card plays aimed at promoting biomimicry, sparking interest and inspiration, or serving as introductory training tools to general public (Biomimicry 3.8 2016, Circulab 2018). This shows that the quality and quantity of scientific information are not only affected by the tool type but also depend on the design intention, application context, and target user of a tool. A direct link between the quality and quantity of scientific knowledge and the effectiveness of a tool is not expected to be found.

Only E2BMO (BT-16) scored a 3 for biological strategies coverage (C7), providing between 100 and 1000 strategies (McInerney *et al* 2018). Two tools (BT-14 and BT-23) scored a 4, both representing the AskNature database, with around 1700 strategies (Deldin and Schuknecht 2013). The five tools (BT-02, BT-03, BT-07, BT-09, and BT-21) that scored highest for biological strategies, providing over 5000 strategies, all share the common feature of having programs that can access automated databases. For example, BiOMIg Search combines algorithms and AI to collect and analyze various publicly available biological papers online, ultimately presenting them to users. This allows it to access data from millions of documents (BiOMIg Search 2024). Similarly, BIDARA, although it does not have its own database, uses ChatGPT as its core, thus inheriting the extensive data from ChatGPT's training set (Nasa-Petal 2023). These tools leverage advancements in AI and other computational methods to process vast amounts of data, enabling them to cover a vast number of biological strategies that were previously unattainable. This pattern indicates a link between the type of tool and its capacity to provide biological strategies. Developers of computational tools aim to expand the breadth of biological strategy coverage, enhancing the tool's knowledge capacity. This expansion is facilitated by technological advancements in computational platforms and databases.

However, a high quantity of biological strategies does not always align with a high quality of scientific information. Among the five tools scoring the highest in strategies coverage, their scientific foundation (C8) ratings are mixed: two scored 2 (BT-02 and BT-03), two scored 3(BT-07 and BT-21), and only BiOMIg Search (BT-09) scored 4 (figure 8). Although AskNature provides less than 2000 strategies compared to the five tools with larger databases and wider biology strategies coverage, it scores 4 in the scientific foundation, indicating a relatively high quality of information through its information screening process, as well as regular maintenance and updates to ensure reliability (Deldin and Schuknecht 2013).

Current tools with databases provide a multitude of biological strategies, but they tend to highlight only the most prominent strategies of the most notable species. For example, when searching the term 'lotus' or 'gecko' in BiOMIg Search, strategies associated with the lotus often focus on its self-cleaning and hydrophobic properties, and gecko strategies emphasize the adhesive ability of their foot (BiOMIg Search 2024). While the gecko's adhesive ability is a classic biomimetic strategy, other characteristics such as its communication skills, hunting strategies, and tail mechanisms (Chellapurath *et al* 2022) are also potential sources of inspiration but are often overlooked in certain tools. The richness of species diversity and the variety of traits within a single species are not fully represented (Stuart-Fox *et al* 2023). AI automated systems have the potential to transform this gap in significant ways. When strategies are manually curated or through preset filters without AI, popular strategies (strategies with more publications and references) naturally dominate. For example, a search in Scopus reveals significantly more results for 'gecko adhesion' (1112 documents found) compared to 'gecko autotomy' (79 documents found); when combining these two terms with the 'biomimetic' keyword, the disparity in results becomes even more pronounced (335 documents compare to 1 document), this search was performed on 5th August 2024. The pre-selection of popular strategies enhances the taxonomic bias that is evident in biodiversity data favoring popular organisms and functions through societal preferences (Jacobs *et al* 2014, Troudet *et al* 2017, Hund *et al* 2023). The integration of AI might offer a less biased selection of biological strategies, thus having the opportunity to suggest rare strategies for specific needs. For instance, when users clearly articulate their technological requirements (e.g. designing a separation mechanism), AI tools can not only provide strategies related to gecko adhesion but also draw upon relevant principles from gecko tail autotomy among others; or remind users there are other gecko species with greater potential apart from the favorable model specie Tokay gecko (Russell and Garner 2021). This means that the number of publications regarding certain biological models would no longer be the sole criterion for sorting and selecting strategies, potentially better addressing the complexities of biomimetic product development requirements.

3.2.5. Integrated insights on self-sufficiency information index and reproducibility

The combination of results from reproducibility (C10) and self-sufficiency (C9) assessments was analyzed to test the hypothesis: whether a higher self-sufficiency index, meaning an easily operable tool with adequate usage information, would lead to a high reproducibility rate and stable outcomes. However, this hypothesis does not hold true as no statistically significant correlation was found. Despite this, reproducibility appears to follow a pattern correlating with tool types (figure 9).

Structured workflow templates tend to have a low score in reproducibility, with the only exception being Biomimicry DesignLens (Life's Principles) (BT-12). These tools typically serve as guiding templates with high flexibility, for instance, the KoMBi approach (BT-19) presents key questions on the template, allowing users to freely interpret and fill in their responses. This openness results in lower reproducibility scores, reflecting the variability in user input and interpretation. The self-sufficiency information index appears neither type nor reproducibility linked. Tools providing extensive biological strategies, such as those integrating AI and automated databases, offer a wealth of information, but their reproducibility varies based on their design. Of the physical/analogous tools, cards and catalogues show high indices in self-sufficiency, but only catalogues offer reproducible results. While data retrieval tools (e.g. Bioinspire-Explore, BARcode, BiOMIg Search) are expected

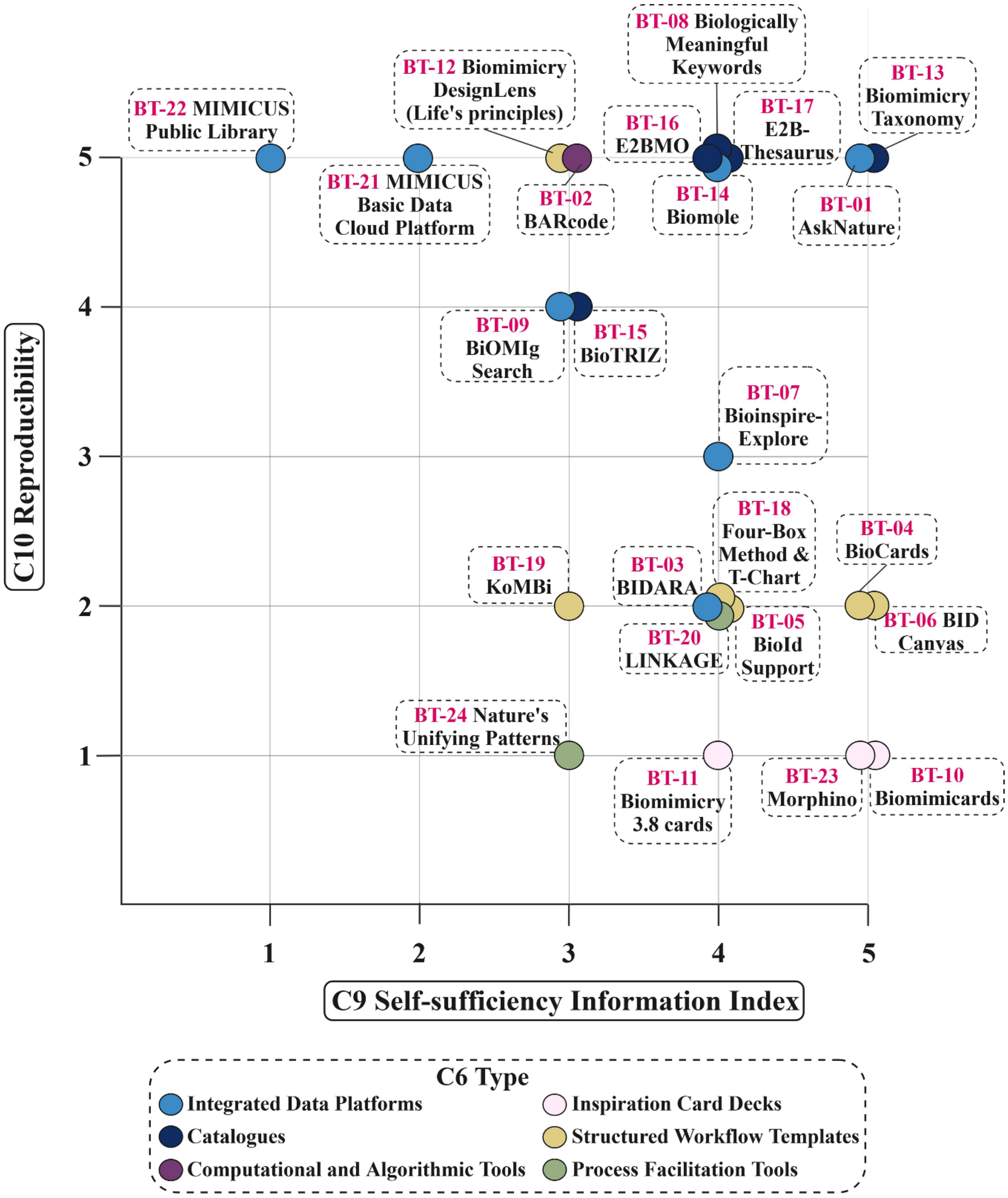

Figure 9. Integrated overview of self-sufficiency information index (C9), reproducibility (C10) and type (C6). Note that all scores are integers- overlapping circles in the figure indicate that multiple tools share the same score for the two criteria, occupying the same coordinate point.

to produce consistent results, inspiration tools (e.g. Morphino, Biomimicry 3.8 cards, Biomimicards) benefit from generating diverse outputs.

4. Conclusions

The assessment of 24 current biomimetic tools across 10 criteria provides a detailed overview of their characteristics, and a method of tool definition and classification. The assessed tools could be grouped into six established types: Integrated Data Platforms, Catalogues, Computational and Algorithmic Tools, Inspiration Card Decks, Structured Workflow Templates, and Process Facilitation Tools. The majority of the criteria results which describe tool characteristics, are linked to the tool's type (with the only exception being C9 Self-sufficiency Information Index). This enables predictions of a tool's characteristics based on its typology. The landscape of biomimetic tools evolved in time with distinctive trends in tool types towards digitization, which allows a prediction that more computational tools will emerge in the format of interactive data platforms in the coming 5–10 yrs.

Developing tools with advanced computational methods can enhance their capacity of providing more robust and extensive solutions. Tools like BiOMIg Search and BIDARA demonstrated how leveraging AI and extensive data repositories can substantially enhance the coverage of biological strategies and assist in maintaining the relevance and accuracy of the information provided. The increasing integration of AI and other computational methods in recent tools signifies a pivotal shift in the biomimetics field. Following this shift alongside technological advances, new tool types can be expected to emerge in future as well.

The assessed tools cover a wide range of functionalities catering to various needs within the biomimetic process, from ideation and inspiration to biological analysis and practical implementation. For each step, there is at least one tool facilitating the required task. By understanding the specific strengths of each tool, practitioners can select the most appropriate tool for their needs. Nevertheless, a lack of tools in technical specification and assessment classes remains, indicating areas for future tool development. Addressing these gaps can provide more support for practitioners. As demonstrated by BIDARA- the only tool of this study covering all classes within the biomimetic process- AI can facilitate the integration of multiple or all steps of the biomimetic process. This shows another avenue for future research: whether creating tools that cover multiple classes/steps of the biomimetic process, from analysis and abstraction to implementation and assessment, are more effective than tools that specifically address fewer classes for users.

The assessment revealed a broad spectrum of tool maturity, with many tools in the open testing phase. This indicates an active phase of development and iteration, with tools evolving rapidly. However, it also highlights the lack of tools that have been validated through practical applications (and documented in public records thus making such information accessible to the authors of this study). Further research can focus on gathering empirical data through user testing and practical validation to better understand the real-world applications of biomimetic tools. Best practice examples demonstrating the successful use of certain tools in biomimetic projects could provide great value for other practitioners with similar goals or project approaches. The authors aim to explore these aspects in future research by engaging practitioners and testing key tools in active projects, helping to close this critical gap in the field.

The high proportion of freely accessible tools reflects a strong incentive within the field to make biomimetic tools widely available to practitioners. While the principles of open science reflect a collaborative environment, the lack of integration of existing tools into novel tools suggests potential gaps in this collaboration. Tool developers can learn from and utilize existing tools. The 104 items listed in appendix 2 represent diverse ideas, theories, and concepts which can be used as a basis for developing new tools, thereby saving resources and development time, and fostering collaboration. For instance, combining semantic tools including thesauri and ontologies- like E2BMO- with a biological strategies database, could enhance the value of these tools for the biomimetic process. To gain a deeper understanding of these collaboration potentials, it would be beneficial to cross-compare the affiliations of developers, among other factors, to assess the true extent of collaboration within the community in future research.

Many valuable tools, such as DANE (Vattam *et al* 2011), SAPPhIRE (Chakrabarti *et al* 2005, Srinivasan and Chakrabarti 2009), and IDEA-INSPIRE (Chakrabarti *et al* 2017, Siddharth and Chakrabarti 2018), exhibit rigorous scientific foundations and have significantly influenced the biomimetic tool research field. However, they have gradually faded from prominence or remain confined to specialized academic papers. Tool development is often constrained by project timelines and resources, ceasing with the project's conclusion. This study indicates that a tool requires certain characteristics to stay relevant and become widely recognized and utilized in biomimetic projects and product development. Firstly, in terms of accessibility, tools should extend beyond academic literature. Many well-designed tools remain underutilized due to their limited exposure in scientific publications. Interactive online platforms, on the other hand, offer advantages in findability and accessibility. Secondly, the tool's functionality is crucial. 'Traditional' tools typically pursue one of two objectives: (a) to remain open-ended, for example, inspiration cards or canvases with open-ended questions and thereby foster creativity, as innovation thrives on unrestricted idea generation or (b) to establish rigid frameworks, helping users streamline their processes and achieve results more directly. These two contrasting approaches both demonstrate their respective values. For academic research, a diversity of tools can be essential to stimulate the development of the field (Wanieck *et al* 2017). However, when it comes to practical product development, the requirement is leaning toward an accessible system that combines inspiration with structured guidance (Fayemi *et al* 2017), covering the entire spectrum between these two extremes. Such tools would be beneficial for practitioners from diverse backgrounds, including engineers, biologists, product designers, etc. (Graeff *et al* 2021a). Additionally, a focus on improving interactivity and user engagement can enable practitioners to navigate and utilize these biomimetic tools more effectively. Looking ahead, the most promising direction for biomimetic tool development is the creation of interactive online platforms that include biological strategy databases and support both problem-driven and solution-based approaches. Tools that understand natural language and can seamlessly switch between inspiring creativity and providing directional guidance hold immense potential. Currently, all tools are either designed for problem-driven processes or can be applied in both approaches, while no tools are designed specifically for solution-based approaches. Despite the success of well-known biomimetic products like VELCRO® and the lotus effect, which are outcomes of solution-based processes, this approach remains underexplored. The combined diagram for both approaches established in this publication (figure 5) could support the development of the solution-based process and its tools. Moreover, the newly established and integrated class of assessment provides an entry point for the creation of new biomimetic tools. Even though sustainability was not explicitly assessed as a criterion in this study, it is evident that the current tools do not seem to directly focus on enhancing sustainability outcomes. Given the growing importance of sustainable design, future (assessment) tools could benefit from incorporating sustainability metrics.

Based on the tools' typology trend across recent years, the demonstrated capacity benefits for biological strategy databases, and the breadth of process coverage exemplified by AI-powered tools, one conclusion is clear: the development of AI-based biomimetic tools is a key area for future innovation. AI, particularly since the advent of ChatGPT, has gained immense popularity, sometimes appearing as a 'hyped' trend (Owens 2023, Council of the European Union: General Secretariat of the Council 2023). However, its undeniable value lies in its capability to effectively address the intricate demands of biomimetic projects. Tools like BIDARA, which utilizes prompt engineering based on ChatGPT, or BiOMIg Search, which employs integrated AI engines, have shown impressive performance. The potential for AI, combined with biological strategy databases and various biomimetic frameworks, represents a significant avenue for future development.

The field of biomimetics is continually evolving, with new tools being developed and existing ones updated. The findings in this paper represent a snapshot in time, and the sketched landscape is expected to change within the coming years. By addressing the above-mentioned areas, the biomimetic community can continue to develop innovative tools that support and advance the field, fostering greater collaboration and application of nature-inspired solutions in various domains.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

This work was financially supported by the European Union's HORIZON-MSCA-DN-2021 under Grant Agreement No 101073100, and the Deggendorf Institute of Technology (DIT). The authors are grateful for the financial support.

The authors are also thankful to Raoul Van Damme from the FunMorph lab of the University of Antwerp, Anick Abourachid and Pauline Provini from the MECADEV department of the Muséum National d'Histoire Naturelle Paris, for their guidance and support.

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