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PATENT-PAPERS MATRIX, S-CURVES, AND HYPE CYCLE APPLIED TO PROTOTYPES IN THE AGRO-INDUSTRIAL CHAIN OF COCOA (Theobroma cacao L.)

Jhon Wilder Zartha Sossa[1] ; María del Pilar García Mendoza[2] ; Fabio Andrés Coral Jiménez[3] ; Jhoan Sebastián Rodríguez Torres[4] ; Andrés Felipe Arias Medina[5] ; John Fredy Moreno Sarta[6] ; Luis Horacio Botero Montoya[7]

[1,4,5,6,7] Universidad Pontificia Bolivariana - UPB, Colombia, jhon.zartha@upb.edu.co , jhoan.rodriguez@upb.edu.co , andres.ariasm@upb.edu.co , johnmorenosarta@gmail.com , lhbotero@gmail.com

[2,3] Centro de Desarrollo Tecnológico Agroindustrial – CDTA, Colombia, maria.garcia6@utp.edu.co , facj_199@utp.edu.co

Abstract*– Agro-industrial sectors must identify technologies and innovations through technology management approaches that enhance efficiency, competitiveness, and the quality of life of agricultural producers, associations, and other stakeholders. This study aims to identify and prioritize technologies and innovations related to the cocoa agro-industrial chain in support of technology transfer processes. To this end, technology management methods were applied to assess the viability of emerging prototypes in this chain by combining S-curves, the Patent-Papers Matrix, and the Hype Cycle. The methodological approach included the definition of critical watch factors (CWFs), the construction of five Scopus search equations for the chain, time-series analysis, and nonlinear regression modeling in Sigmaplot. Emerging components were identified through the Hype Cycle from the perspective of associations. The S-curve analysis yielded inflection points between 2019 and 2035, revealing different stages of technological maturity. The cocoa chain exhibited an overall maturity stage, with most equations reaching patent inflection points between 2019 and 2020; C5 (cadmium in cocoa) stood out because scientific research is projected to continue expanding through 2034. The Patent-Papers Matrix placed the technologies in the lower-left quadrant, highlighting opportunities for incremental and process innovation, and in the lower-right quadrant, where opportunities emerge for the commercialization and scaling of patented technologies, the monitoring of emerging science, and collaborative applied research with industry to strengthen existing patents and promote academia-industry collaboration.

Keywords*-- Innovation management, cocoa, S-curves, Patent-Papers Matrix, Hype Cycle.

I. INTRODUCTION

[1], [2]Latin America and the Caribbean are characterized by a broad supply of agricultural and agro-industrial products, enabled by the biotic and abiotic diversity of their territories. This diversity supports the cultivation of native crops that are highly relevant to local economies and increasingly attractive to consumers worldwide. Cocoa is one of these crops. [3], [4][5][6][6][7], [8]Cocoa (*Theobroma cacao* L.) is one of the most relevant agricultural products in the region because its production and consumption have grown steadily over recent decades. This tropical species, native to the Upper South American Amazon, accounts for global production exceeding 5 million tons per year, with Africa (65%) and South America (21%) as the leading producing regions. Ecuador ranks fourth worldwide and first in South America, followed by Brazil, Peru, and Colombia. In these countries, the cocoa chain is a strategic component of the agricultural sector; accordingly, there is a growing need for studies that address the sector's main challenges, opportunities, and priority issues in a strategic manner.

Accordingly, this study seeks to identify and prioritize technologies and innovations related to the cocoa agro-industrial chain. It examines technology management (TM) methodologies applied to prototypes derived from this chain, with special attention to the analysis of technological trends through S-curves, inflection points, the Patent-Papers Matrix, emerging components, and the Hype Cycle.

The methodology is organized into three main phases addressing core aspects of the TM and innovation process. Phase 1 comprised planning and the collection of relevant information, including the definition of critical watch factors (CWFs), which were validated with expert support before the search equations were developed. In Phase 2, five Scopus search equations were constructed, generating five time series for articles and patents. In Phase 3, S-curves were modeled for those time series and inflection points were calculated from cumulative article and patent series using the free version of Sigmaplot V16, Python libraries, and nonlinear logistic regression code. This phase also produced the Patent-Papers Matrix from the inflection-point data and two Hype Cycles for analyzing emerging components.

II. THEORETICAL FRAMEWORK

[5], [6][9], [10]Cocoa production is broadly distributed across the two principal producing regions, Africa and South America, where the crop has major economic and social relevance within the agricultural sector. The challenges currently facing primary producers are especially significant, including climate change, pest and disease management, low soil fertility, and high cadmium levels, all of which threaten the sustainability of local chains and the quality of the raw material.

[10], [11][12][13]High cadmium levels have become a major concern because this metal has been detected in food products—especially chocolate—and its high mobility in soils facilitates plant absorption and bioaccumulation. Cadmium is classified as a heavy metal with serious implications for human health because of its toxicological and carcinogenic effects. In response to concerns over elevated cadmium content in chocolate products, the European Union established maximum limits for imported cocoa-based products; consequently, cadmium has become a priority issue for stakeholders across the cocoa sector.

[14], [15][16], [17][18][15], [17], [19], [20], [21]Value addition in cocoa processing involves key stages such as fermentation, drying, and roasting. During fermentation, cocoa beans develop flavor precursors and their germination is inhibited by physicochemical changes and temperature increases caused by bacterial and yeast activity. The fermented beans then undergo drying, either in natural or artificial dryers, to stop fermentation, further develop flavor and color through enzymatic browning, and extend shelf life by reducing moisture content to approximately 7%. The dried beans are subsequently roasted, and under high temperatures (120–190 °C), moisture is reduced to around 2%, the shell separates, and the characteristic dark brown color and aromatic compounds are developed from precursors formed in the previous stages. These operations strongly influence the physicochemical properties, sensory quality, and shelf life of the derivatives obtained in later processing stages.

[22], [23][18], [23], [24]Cocoa yields a wide range of value-added derivatives, especially chocolate and cocoa liquor. Cocoa liquor results from grinding cocoa nibs (roasted, dehulled, and broken cocoa beans) and serves as a raw material for the manufacture of multiple chocolate products. This explains the growing importance of assuring cocoa quality, as well as the quality of the postharvest and processing technologies involved, in response to an increasingly demanding and expanding market.

[5], [6]For these reasons, cocoa is regarded as a strategic crop of both global and regional importance that engages multiple actors across its agro-industrial chain. Consequently, there is a clear need to broaden the body of studies that address the sector's main challenges, opportunities, and priority issues from a strategic perspective.

Technology Watch and S-Curves

[25][26]][27][28][29]Innovation and technology management have consistently underscored the importance of understanding key organizational dimensions through a multidimensional approach that includes knowledge, technology, innovation, development, research, and resources, among others, each with strategies tailored to its particular scope. Within this framework, TM—and, in parallel, technology watch as an organized process for capturing, analyzing, and transforming external information into knowledge—emerges as an essential tool for promoting innovation by identifying opportunities and new ideas applicable to the chains studied and their subproducts. Similar studies in cocoa, avocado, plantain, and vegetable chains, as well as in other agro-industrial by-products such as tanning, show that technology watch combined with S-Curve analysis offers advantages such as market anticipation, risk reduction, cooperation, and the generation of new projects.

[30]The different forms of watch focused on technological, market, customer, supplier, environmental, product, and competitor dimensions help identify critical watch factors (CWFs), which in turn support optimized and better-planned decision-making. These CWFs serve as inputs for formulating the search equations used in this study, together with Boolean operators applied in Scopus and Lens Patents, which contain journal articles and patents along with metrics relevant to research and decision-making.

[31][29], [32]Based on the number of retrieved articles and patents, the S-Curve methodology was applied in view of its wide range of uses, from projecting the performance of new technologies to analyzing market penetration, forecasting demographic change, conducting macro- and microeconomic analyses, and examining technological diffusion mechanisms. It is also useful for identifying technological life-cycle stages, determining the appropriate timing for intellectual property and technological rights actions, and defining monitoring and investment strategies. In this sense, S-Curve-based models play a central role in understanding the dynamics of change by revealing patterns, causes, probabilities, and possibilities across social, political, economic, and technological systems.

Hype Cycle

[33]To assess the impact of new technologies from an organizational perspective, the Hype Cycle methodology is used, highlighting its contributions and suggesting possible future lines of research. This model is built through the combination of equations and bell curves related to expectations, which are established as a sudden, positive, and

irrational response to the existence of a new technology. Experts
[34]argue that the configuration of this curve is due to three phenomena of human nature: attraction to novelty and the desire to share it, social contagion, and the generation of new knowledge in decision-making, and that these phenomena can also enhance a new technology.

[35][36]Introduced by Gartner Inc. in 1995, the Hype Cycle model traces an applicable path that illustrates the evolution of technology in relation to expectations and the viability of technological value over time. Its relevance highlights that the S-Curve-based diffusion model has predominated in innovation evolution research and practice for almost six decades and, despite its wide acceptance for more than 20 years, the academic literature has scarcely confirmed the Hype Cycle phenomenon as described. In their study entitled “The role of expectation in innovation evolution: Exploring hype cycles,” this article integrates innovation diffusion with Hype Cycles through an interdisciplinary conceptual framework that explores how expectations influence the early stages of innovation adoption.

The construction of the Hype Cycle, traditionally dependent on expert inspection of large volumes of information, was this time supported by a computational workflow implemented in Python that integrates the programmatic retrieval of news through aggregation services, sentiment analysis per article based on the VADER lexicon, and the annual aggregation of mentions for each technology under analysis. From the annual series, the relevant inflection points, the year of sustained appearance, the peak of mentions, and the subsequent trough were automatically identified by means of statistical criteria applied to the cumulative count and its percentage variation, which made it possible to assign each technology to its corresponding phase with an associated confidence indicator. This computational treatment substantially reduces the time required compared with manual processing and enables the replication of the analysis over updated time windows without modifying the procedure, with a view to becoming a complete product for foresight studies.

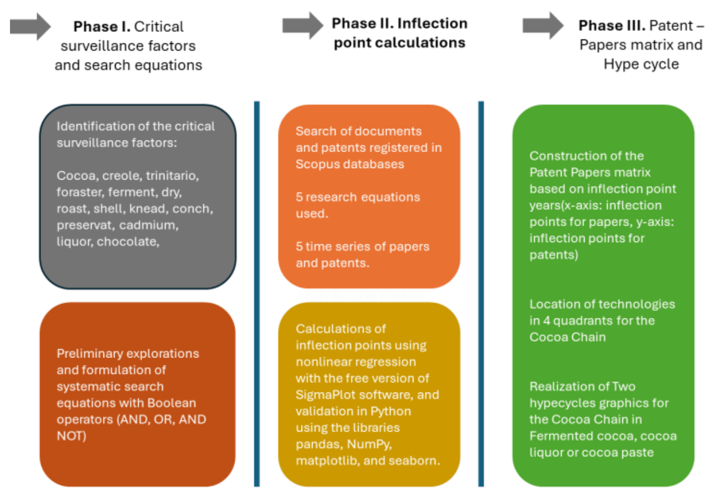
Patent-Papers Matrix / Quadrants

The Patent-Papers Matrix / quadrants makes it possible to refine the calculations of S-Curve inflection points, generating four quadrants in which technologies are positioned according to their opportunities and providing valuable information on technologies with inflection points on the article and patent axes.

III. METHODOLOGY

[38][39]The three phases proposed in this study address key aspects of the process. Their structure had previously been applied by , following the guidelines suggested by , and includes stages for planning, capturing, and searching for critical watch information, as well as an analysis and intelligence-generation stage composed of S-Curve analysis, the Patent-Papers Matrix, and the Hype Cycle. This sequence makes it possible to obtain, document, report, and compare research behavior over time with previous agro-industrial studies on the topic. Fig. 1 presents the phases of the methodology.

The application of S-Curves, the Patent-Papers Matrix, and the Hype Cycle is justified for several reasons. S-Curves, built from cumulative time series of papers and patents, support decisions on the stage a technology has reached, the timing of intellectual property actions, and the definition of monitoring and investment strategies. The Patent-Papers Matrix refines inflection-point calculations derived from S-Curves by generating four quadrants that position technologies according to their opportunities and summarize, in a single framework, technologies with future inflection points on the paper and patent axes. Finally, the Hype Cycle helps identify emerging components from social media according to the year in which they occur, thereby complementing the analysis based exclusively on papers and patents.



[37]**Fig. 1. Proposed methodology. Adapted from .**

Phase 1: The CWF that identifies the different topics and fundamental requirements for the development of the article was established by researchers from the Centro de Desarrollo Tecnológico Agroindustrial of the Universidad Tecnológica de Pereira (CDTA-UTP) with experience in agro-industrial engineering, process engineering, and agro-industrial chains, and with postgraduate training.

Preliminary explorations were carried out continuously, followed by the formulation of systematic search equations, using as sources the documents and patents recorded in the Scopus databases. The search was conducted in the title, abstract, and keywords fields (TITLE-ABS-KEY).

Phase 2: Five search equations were developed in Scopus for the chain on the basis of the CWFs (Table I). These equations generated five time series for articles and patents, which served as inputs for calculating inflection points through nonlinear regression using the free version of Sigmaplot and validation in Python with pandas, numpy, matplotlib, seaborn, and sigmoid-function code.

The retrieval of the time series was carried out by means of programmatic queries to the application programming interfaces (APIs) of the consulted databases, which made it possible to preserve the traceability of each search equation and facilitate its subsequent replication under the same query conditions.

Table I.
Search equations based on the CWFs.

Chain	Equation	ID
Cocoa	(TITLE-ABS-KEY(fine AND cocoa) OR TITLE-ABS-KEY (creole* AND cocoa*) OR TITLE-ABS-KEY ("trinitario*") OR TITLE-ABS-KEY ("foraster*") AND ALL("ferment* method¨*" OR "dry* process*"))	C1
	(TITLE-ABS-KEY (fine AND cocoa) OR TITLE-ABS-KEY (creole* AND cocoa*) OR TITLE-ABS-KEY ("trinitario*") OR TITLE-ABS-KEY ("foraster*") AND TITLE-ABS-KEY ("ferment*" OR "dry*" OR "roast*" OR "shell*" OR "knead*" OR "conch*" OR "preservat*"))	C2
	(TITLE-ABS-KEY (fine AND cocoa) OR TITLE-ABS-KEY (creole* AND cocoa*) OR TITLE-ABS-KEY ("trinitario*") OR TITLE-ABS-KEY ("foraster*") AND TITLE-ABS-KEY("cocoa butter" OR "cocoa liquor" OR "chocolate topping*" OR "cocoa cake*" OR "dark chocolate"))	C3
	(TITLE-ABS-KEY (fine AND cocoa) OR TITLE-ABS-KEY (creole* AND cocoa*) OR TITLE-ABS-KEY ("trinitario*") OR TITLE-ABS-KEY ("foraster*") AND ALL ("aroma* profile*"))	C4
	(TITLE-ABS-KEY ("cocoa") AND TITLE-ABS-KEY("cadmium"))	C5

Source: Authors' own elaboration.

Phase 3: Effective innovation and technology management is essential for the sustainable development of firms in the contemporary era. This article examines three key methodologies applied to the cocoa agro-industrial chain—S-Curves, the Patent-Papers Matrix, and the Hype Cycle—and highlights their relevance for strategic innovation management.

[30], [31]Article and patent data were organized into tables showing years and counts. These values were accumulated and entered into Sigmaplot (30-day free version). The software's 13 nonlinear models were then applied to derive S-Curves. Curve validity was assessed using the program's statistical outputs, including adjusted R^2, t values, p values, and the Durbin-Watson statistic, in accordance with criteria previously evaluated in different studies and application areas. After obtaining the second derivative for each equation, the life cycle of the selected technologies was analyzed on the basis of the resulting inflection points, allowing the most appropriate curves to be selected and interpreted in greater detail.

Additionally, the fitting of the sigmoid models was automated in Python through routines based on scipy.optimize, which made it possible to process the five search equations in parallel and obtain the goodness-of-fit statistics (adjusted R^2, t and p values, Durbin-Watson) in a reproducible manner, following the validation criteria established in [30], [31].

The Patent-Papers Matrix provides an integrated means of evaluating the effectiveness of an R&D&I strategy. By examining the relationship between scientific publications and patents, it helps align research activity with the innovation objectives of organizations or associations and offers a broader basis for future decisions. The matrix is interpreted through four quadrants, where the X-axis represents the inflection point for articles and the Y-axis represents the inflection point for patents. Its construction uses the year in which the calculations associated with the search equations were performed.

[33]The Hype Cycle methodology, in turn, offers a systematic framework for evaluating the adoption of emerging technologies over time. With phases such as the peak of inflated expectations, the trough of disillusionment, and the plateau of productivity, the Hype Cycle becomes a valuable tool for informed decision-making regarding the adoption of new technologies in organizational settings. Its effective use requires a holistic perspective, since combining these tools provides a more comprehensive basis for strategic decision-making in innovation management.

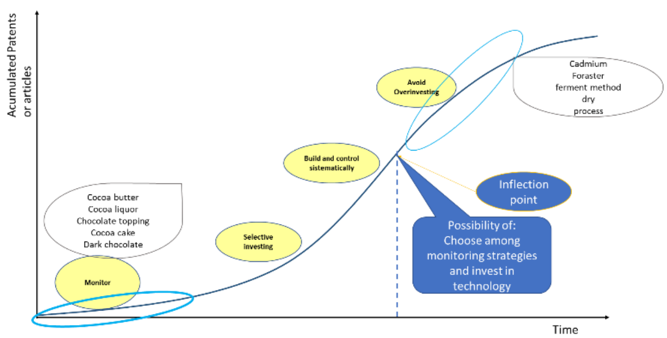
The construction of the Hype Cycle, which traditionally demands intensive manual processing for term extraction, the estimation of mention peaks, and the assignment of each technology to its corresponding phase, was supported by natural language processing routines and temporal frequency analysis implemented in Python, which made it possible to standardize the criteria for placement on the curve and reduce the subjectivity inherent in manual inspection.

IV. RESULTS

Phase 1—planning, information gathering, and information search—generated the inputs required for the subsequent methodological phases. An initial compilation of the expert-proposed CWFs was therefore carried out, taking as its guiding criterion the identification of the topics and needs of the agro-industrial chain under study. The compiled CWFs were then analyzed and used to build the search equations entered into Scopus. Finally, the results retrieved from those searches were refined and categorized.

A. Analysis of S-Curves and Inflection Points

In Phase 2, tools and methodologies were implemented to process and analyze the information obtained in Phase 1. Table II reports the search equations used to determine the number of articles and patents indexed in Scopus and their respective inflection years, thereby allowing the behavior and status of the technologies to be understood over time. Figure 2 illustrates the technological phases represented within the S-Curve for the topics associated with the search equations used.



[32]**Figure 2. Technology life cycle and evolution. Key factors found for papers. Adapted from .**

Once these data had been obtained, 13 nonlinear regression models were applied to the annually accumulated data using the free version of Sigmaplot. Hypothesis testing was then performed through t and p values, together with the calculation of Durbin-Watson statistics. The results identify the technologies that stood out under the methodologies applied and indicate their performance potential and current position within the technological life cycle.

Table II.
Research situations for articles, patents, and inflection points.

Chain	ID	Papers	Patents
	C1	2022	2020
	C2	2035	2020
Cocoa	C3	2035	2020
	C4	2025	2020
	C5	2034	2019

Source: Authors' own elaboration.

[40]The results indicate a mature technological landscape in the cocoa chain. Equation C1, related to fermentation and drying methods, and equation C4, focused on aroma profiles, both present past inflection points for Papers and Patents. These patterns suggest that these technologies have already entered a technological maturity stage in which both scientific research and patenting activity have moved beyond thei
r period of accelerated growth.
Equations C2, C3, and C5, associated respectively with transformation processes, cocoa-derived products, and cadmium in cocoa, showed future inflection points in 2034 and 2035; nevertheless, their patent activity indicates consolidation and maturity.

B. Patent-Papers Analysis

[34]Regarding the results of Phase 3, the Patent-Papers Matrix (Fig. 3) was used to evaluate the effectiveness of R&D&I strategies. Its construction considered the time horizons obtained from the search equations, using 2026 as the reference year for the calculations. The matrix is based on the inflection points/years reported in Table II: when article and patent inflection points are earlier than 2026, the equation is positioned in the lower-left quadrant, whereas equations with article inflection points after 2026 and patent inflection points before 2026 are placed in the lower-right quadrant.

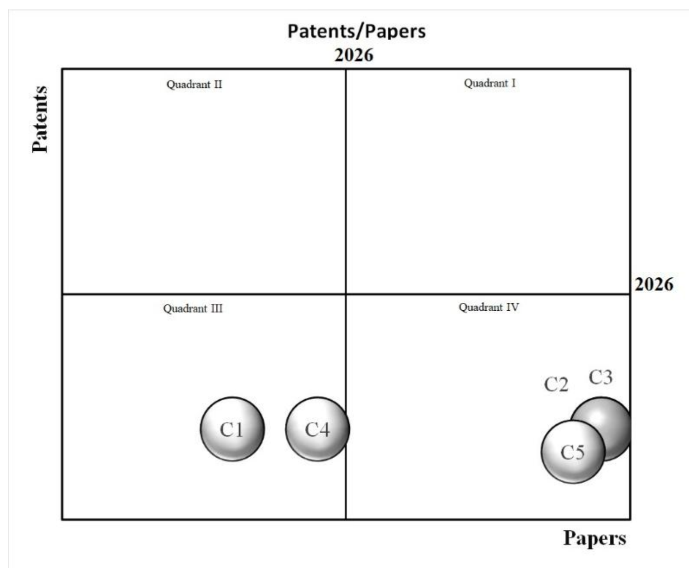


Fig. 3. Patent-Papers Matrix for the cocoa chain. Source: Authors' own elaboration.

[40]As shown by the matrix, the topics studied in the cocoa chain display a characteristic pattern of technologies at different stages of maturity. Based on , Table III summarizes how the location of each equation in the Patent-Papers Matrix can be interpreted.

Table III.

Interpretation of the location of the equations in the quadrants of the Patent/Papers Matrix

Quadrant	Equations	Interpretation
III	C1, C4	Established technologies and competitive markets. The scientific base and key intellectual property are consolidated.
IV	C2, C3, C5	Industry moved faster to protect applications, but foundational research is still under development. A field driven by practical applications.

[40]Source: authors' own elaboration based on .

C. Hype Cycle Analysis

[41]Subsequently, using the Hype Cycle methodology based on the initial model proposed by , each emerging technology was interpreted as following a five-phase trajectory that reflects its evolution over time. The cycle begins with innovation, characterized by potential technological breakthroughs, although useful products are often not yet available and commercial viability remains uncertain. The second phase corresponds to the peak of inflated expectations, when initial publicity gives rise to a combination of notable successes and some failures. The third phase is the trough of disillusionment, in which interest declines as applications and experiments fail, and investment continues only if surviving suppliers improve their products enough to satisfy early adopters.

[42],[41]The Hype Cycle analysis based on social media data for fermented cocoa (Fig. 4a) and cocoa liquor or paste (Fig. 4b) reveals the temporal evolution of market expectations and technology adoption in these specific segments of the production chain. For fermented cocoa, the cycle spanned 2014–2022 and followed a trajectory consistent with the Gartner model. The trigger stage (2014–2016) was dominated by fermentation methods and double-fermentation products, whereas the peak of expectations (2017–2019) emphasized applications involving specific microorganisms such as Saccharomyces cerevisiae 9D, in line with the rise in studies on microbiological control reported in the literature. The subsequent consolidation and plateau stage (2020–2022) concentrated on infrastructure technologies (stainless-steel dryers and automation) and functional applications (natural probiotics), suggesting a transition from experimentation toward the implementation of integrated technological solutions.

Cocoa liquor or paste displayed a multi-cycle pattern (2010–2022) with two differentiated peaks. The first cycle (2010–2015) focused on gourmet products and high-quality cocoa liquor, whereas the second (2016–2019) shifted toward functional chocolates with specific health claims, such as dark chocolate and regulatory products. The consolidation phase (2020–2022) showed a clear emphasis on functionality and health through fat-free and sugar-free chocolates and fortified products, reflecting consumer demand for products that combine indulgence with nutritional benefits.

Comparing the two Hype Cycles reveals fundamental differences: fermented cocoa is associated mainly with process innovations and primary transformation technologies that require greater initial investment, whereas cocoa liquor or paste is more closely linked to final-product innovations with shorter development cycles. Notably, both cycles accelerated in 2020–2022, coinciding with the post-pandemic period and suggesting that changing consumption habits stimulated faster development. The concentration of innovations on the plateau of productivity indicates that the sector is currently well positioned for technology transfer and prototype commercialization.

Fig. 4. Hype Cycle based on social media: (a) Fermented cocoa; (b) Cocoa liquor or paste. Source: authors' own elaboration.

The Hype Cycle for the analysis of emerging technologies from the perspective of associations can be observed in Fig. 5. As shown in Fig. 7, the topics were concentrated mainly in the launch stage, then on the “slope of enlightenment,” followed by the “plateau of productivity,” and only two technologies, “sensing, drones, and information platforms” and “precision fermentation,” were located at the “peak of inflated expectations.” In this sense, the results provide a broader orientation for strategic decision-making across a wide variety of technologies, highlighting the opportunities represented by technologies in the early stages of the Hype Cycle.

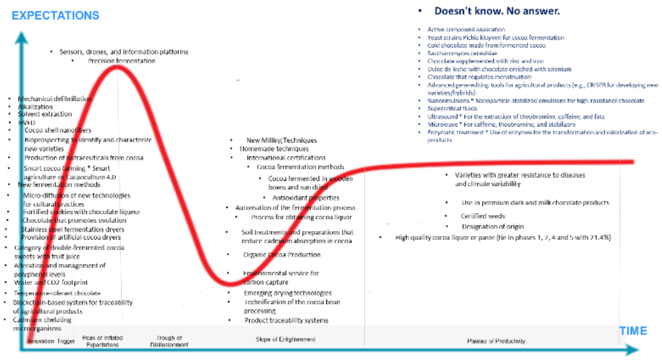


Fig. 5. Hype Cycle for the analysis of emerging technologies from associations. Source: Authors' own elaboration.

The comparison between social media and association-based perspectives reveals substantial differences in how technologies are perceived and prioritized. Social media tend to highlight innovations with mass-market appeal and direct benefits for end consumers, whereas associations emphasize technological needs associated with process improvement, environmental sustainability, and chain competitiveness. This divergence underscores the importance of integrating both perspectives when formulating R&D&I strategies for the agro-industrial chain analyzed here.

D. Automated Hype Cycle applied to the search equations

To complement the perspectives obtained from social media and associations, the automated Hype Cycle workflow was applied to the same five search equations used in the previous phases (Table I). Unlike the bibliometric analysis conducted in Scopus, this approach retrieved mentions from indexed news sources over the 2014–2026 window, assuming that media-coverage cycles constitute a valid proxy for market and public expectations regarding each technology.

For each equation, the automated workflow produced an annual time series of mentions, the associated average sentiment, the relevant inflection points, the trigger, the peak, the subsequent trough, and a phase assignment accompanied by a confidence indicator. These structured outputs were then contrasted with a large language model (LLM), which was provided with the aggregated annual series, descriptive statistics, and metadata for each equation in order to:

(i) Validating the temporal coincidence of the detected peaks and troughs with documented events in the cocoa sector
(ii) Identifying possible biases derived from reduced samples in equations with low media coverage
(iii) Enrich the qualitative interpretation of the assigned phases without altering the quantitative values reported by the automated workflow. This assisted contrast yielded a more robust reading of the results by leveraging the data structure generated by the tool as a standardized input for critical interpretation.

It should be noted that the original search equations formulated with Scopus-specific syntax (TITLE-ABS-KEY, the ALL operator, the use of wildcards such as creole* or trinitario, etc.) had to be adapted for input into the automated workflow, whose input scheme corresponds to a list of terms with Boolean operators applicable to news aggregation services. This adaptation preserved the conceptual intent of each critical watch factor—fine cocoa varieties and their association with processes, derived products, aroma profiles, or the presence of cadmium—but required three operational adjustments:

(i) Removal of Scopus-specific field operators.
(ii) Simplification of wildcards not supported by news search engines.
(iii) Consolidation of nested groups into linear structures of terms with an associated operator. The adaptations were made while maintaining the core descriptors of each equation and prioritizing the terms with the greatest thematic specificity.

Table IV consolidates the results obtained, reporting the total number of mentions retrieved, the year corresponding to the coverage peak, the phase assigned by the system, and the associated confidence indicator.

ID	Mentions	Peak year	Assigned phase
C1	16	2021	Slope of enlightenment
C2	13	2014	Slope of enlightenment
C3	49	2025	Peak of inflated expectations
C4	28	2018	Slope of enlightenment
C5	96	2023	Trough of disillusionment

Source: authors' own elaboration based on

The most salient finding corresponds to C5 (cadmium in cocoa), which showed the most robust sample (N = 96) and a clearly delimited media cycle, with a peak in 2023 (33 mentions) followed by a sharp decline by 2025. The assisted contrast indicated that this peak coincides with documented events, independent publications on heavy metals in chocolate products, and related regulatory actions. It also revealed a threefold temporal mismatch across the three analytical lenses of the study: patents had already matured by 2019, the scientific literature is projected to continue growing through 2034, and public attention had already normalized by 2025. This case empirically supports the value of integrating the three techniques as complementary rather than redundant lenses.

Equation C3 (cocoa-derived products) exhibited a recent peak in 2025, after the 2020–2022 consolidation period shown in Fig. 4b. The assisted contrast interpreted this behavior as a second expectations cycle linked to the global cocoa price crisis of 2023–2025, a phenomenon that the earlier manual analysis could not capture because its observation window ended in 2022. Likewise, C4 (aroma profile) showed a peak in 2018, coinciding with the 2017–2019 period in Fig. 4a. This convergence across independent sources and methods provides cross-validation for the procedure.

Finally, equations C1 and C2 yielded small samples ($N \leq 16$), which is consistent with their technical-industrial nature. Both topics concentrate their activity in scientific literature and patents, as reflected in their location in quadrant III of Fig. 3, while their public visibility remains comparatively low. Rather than constituting a limitation, this pattern reinforces the methodological complementarity between classical bibliometric analysis and the news-based Hype Cycle, since each is more informative for different types of technologies.

V. DISCUSSION

[25], [29]The integrated application of S-Curves, the Patent-Papers Matrix, and the Hype Cycle provides a multidimensional view of technological development in the cocoa agro-industrial chain. The methodology made it possible to identify not only the maturity level of specific technologies, but also the gaps between scientific research, intellectual-property protection, and market expectations—factors that are essential for designing effective technology management and innovation strategies.

The computational implementation of the analytical workflow, supported by a REST-services backend, enables periodic updating of inflection points as new bibliometric records are incorporated. This capability is especially relevant given the dynamic behavior of cumulative article and patent series.

Overall, the evidence points to a mature technological landscape for the technologies assessed, as reflected in the concentration of technologies in the lower quadrants of the Patent-Papers Matrix.

[42], [43][21]From the patent perspective, all equations showed inflection points between 2019 and 2020. Using 2026 as the reference year, these findings indicate that the reviewed technologies are in a maturity stage. Under such conditions, technological growth approaches its limit, radical innovations become scarce, and incremental innovations and optimization processes based on accumulated knowledge predominate. In line with this finding, studies such as have developed watch methodologies around technologies such as cocoa fermentation; although those studies report a significant increase in patents and publications over the last decade, our life-cycle interpretation suggests that such technologies are already transitioning toward technological maturity.

The case of C5, related to cadmium in cocoa, is particularly relevant. Its article inflection point is projected toward 2034, whereas its patent critical point was reached in 2019. This temporal asymmetry suggests that cadmium mitigation and control technologies were developed and protected earlier, while scientific research on the issue continues to expand.

Hype Cycle results for cocoa technologies also reveal a broader diversity of maturity states across the technologies analyzed. This diversity enriches strategic decision-making by opening distinct pathways for action across a wide technological spectrum.

The automated Hype Cycle analysis of the five equations exposed a particularly illustrative pattern in C5 (cadmium in cocoa), where the three methodological techniques applied in this study assign different technological ages to the same issue. Patent S-Curves place its maturity in 2019, indicating early development and protection of mitigation technologies; article S-Curves project the inflection point to 2034, showing continued growth in scientific research; and the automated Hype Cycle positions it in the trough of disillusionment, after a clearly delimited media peak in 2023 and a subsequent sharp decline.

[7]Other studies have applied alternative technology management methodologies to this chain. For example, studies such as propose technology foresight approaches such as the Delphi Method and Scenario Analysis. Their findings identify priority issues, technologies, and innovations and formulate future scenarios through consultation with experts and sector stakeholders. These approaches can be complemented by the results of the present study, which help determine the phase reached by the technologies considered and therefore support more appropriate strategic decisions.

VI. CONCLUSIONS

This study established an overview of the technologies associated with the CWFs analyzed for the cocoa agro-industrial chain through the systematic application of technology management tools. The combined use of S-Curves, the Patent-Papers Matrix, and the Hype Cycle enabled a multidimensional understanding of the technological life cycle and facilitated the identification of opportunities for technology transfer and prototype development.

The findings show that a large share of the technologies analyzed are in a maturity stage, as evidenced by patent inflection points between 2019 and 2020. Equations C1 (fermentation and drying methods) and C4 (aroma profiles) showed consolidation in both research and intellectual-property protection, suggesting that radical innovation is limited and that incremental improvements dominate. Equation C5 (cadmium in cocoa) is particularly noteworthy because it displayed a temporal asymmetry: the papers inflection point is projected toward 2034, whereas the patent critical point was reached in 2019. This pattern indicates that mitigation technologies were developed earlier while scientific research continues to expand, reflecting an emerging issue of high relevance for international competitiveness. Equations C2, C3, and C5 were located in the quadrant corresponding to fields driven by practical applications, where intellectual protection is consolidated but underlying research remains under development.

The Patent-Papers Matrix proved essential for aligning research strategy with organizational innovation objectives, since it enables technologies to be positioned in well-defined quadrants that support decisions on investment and project development. This methodology effectively complemented S-Curve analysis by offering a two-dimensional representation of maturity status and facilitating the identification of differentiated opportunities according to the relationship between scientific research and intellectual-property protection.

The Hype Cycle from the perspective of associations added an essential qualitative dimension to the analysis. As observed, the diversity of technologies distributed across the cycle—from launch to the slope of enlightenment and the plateau of productivity—enriches strategic decision-making, especially in the case of technologies such as sensing-drones-platforms and precision fermentation, which are positioned at the peak of inflated expectations.

The social-media-based Hype Cycles for fermented cocoa and cocoa liquor or paste provided an essential complementary perspective on the evolution of market expectations. Fermented cocoa followed a single cycle centered on process innovations such as automation, microbiological control, and infrastructure, whereas cocoa liquor or paste displayed multiple cycles focused on final-product innovations, including functional and fortified chocolates with health-related attributes. The concentration of technologies on the plateau of productivity in both categories, accelerated during 2020–2022, suggests that the sector has moved beyond inflated expectations and is now in a favorable position for technology transfer and prototype commercialization.

Operationally, the incorporation of an automated workflow for constructing the Hype Cycle reduced to seconds an analysis that traditionally requires days of expert work, while preserving reproducible criteria for detecting inflection points and assigning phases. Nevertheless, automation does not replace expert judgment in defining critical watch factors or in interpreting the results strategically. What it does provide is the capacity for systematic updating and greater scalability across larger sets of technologies, together with the possibility of integrating LLMs for deeper analysis.

The results serve as a strategic input for associations, firms, and other actors in R&D&I ecosystems by helping them reduce risk and anticipate market trends. The integrated methodology proved applicable and replicable in other agro-industrial sectors, thereby offering a robust basis for science, technology, and innovation policies aimed at strengthening strategic productive chains. Because inflection points are dynamic, periodic updates are recommended, together with the use of complementary foresight approaches such as the Delphi method to incorporate the perspectives of multiple ecosystem actors.

VII. LIMITATIONS AND POSSIBLE LINES OF RESEARCH

Inflection-point calculations based on articles and patents are dynamic and should therefore be updated over time, since conclusions about the life cycle or stage of a technology may change. The same search formula in Scopus—or equivalent formulas when using other patent databases such as the World Intellectual Property Organization (WIPO), Patent Inspiration, or Free Patents Online—is recommended to maintain comparability.

Although this study incorporated an automated workflow for nonlinear S-Curve fitting, inflection-point extraction, and Hype Cycle construction from news sources, the procedure still presents three operational limitations that define future work. First, media coverage remains insufficient for strictly technical-industrial technologies. Second, the sample size for some equations limits the statistical robustness of phase classification, which is why triangulation with S-Curve analysis and the Patent-Papers Matrix remains advisable. Third, automation should be extended toward the dynamic generation of the Patent-Papers Matrix and integration with multiple patent sources so that the overall analysis can be updated in real time as cumulative series evolve.

The Patent-Papers Matrix could also be used to analyze the technologies, innovations, and knowledge fields of a country, cluster, or organization in order to map and establish investment or prioritization quadrants for decisions related to projects, doctoral thesis topics, technology transfer, and technology acquisition, among other applications.

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