LAB-GROWN CHOCOLATE: CURRENT STATUS AND FUTURE PROSPECTS

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ABSTRACT – *The cocoa and chocolate industry faces severe pressure. Climate change, plant disease, deforestation, and chronic farmer poverty have pushed cocoa futures to record levels and raised doubts about the long-term security of conventional cacao (Theobroma cacao) supply. In response, a group of biotechnology-derived ingredients, referred to here as lab-grown chocolate, has begun to move from the laboratory toward early commercial use. This review examines the current scientific and industry literature on two related but separate routes. The first is plant cell culture, or cellular agriculture, in which dedifferentiated cacao cells are grown in bioreactors to produce cocoa biomass, butter, and powder. The second covers cocoa-free or precision-fermentation analogues, which rebuild the sensory profile of chocolate from non-cacao feedstocks such as oats, sunflower seeds, carob, or grape-seed byproducts. Using recent industry reporting, regulatory filings, university research, and the adjacent peer-reviewed work on cocoa fermentation chemistry and life-cycle assessment, the review describes the state of the technology, the firms and institutions behind it, the regulatory routes under way in the United States and European Union, the main technical obstacles, and the socioeconomic and environmental questions it raises for producing countries. Commercial-scale cell-cultured cocoa products are expected to reach professional and consumer markets between late 2026 and 2027, but real uncertainty remains over cost parity, approval timelines outside the US, consumer acceptance, and the effect of the technology on smallholder livelihoods in West Africa and Latin America.*

Keywords: Cellular agriculture, cultivated cocoa, cell-cultured chocolate, Theobroma cacao, plant cell culture, precision fermentation, cocoa-free chocolate.

INTRODUCTION

Chocolate is among the most widely consumed foods in the world. Its confectionery market generated an estimated $21.4 billion in US sales alone in 2024 and is projected to reach $37.6 billion by 2029 (National Confectioners Association, cited in Fell, 2026). Almost all of that industry depends on one geographically concentrated crop, Theobroma cacao, of which roughly 70-75% is grown by smallholder farmers in Cote d'Ivoire and Ghana. This concentration has become a structural weakness. Cocoa futures rose by 136% between July 2022 and February 2024, and prices reached a record $12,605 per metric ton in December 2024, about 300% above their early-2024 level (Cocoa Runners, 2024; Chocolate Affairs Magazine, 2025). The immediate causes are climatic and biological. Erratic rainfall and drought linked to climate change, outbreaks of black pod disease, and the spread of cacao swollen shoot virus have together killed an estimated 200 million trees in West Africa (Fell, 2026; Ameyaw *et al*., 2024). The deeper causes are structural: aging tree stock, chronic underinvestment in farms, land degradation from deforestation, and a farmgate pricing system in Ghana and Cote d'Ivoire that lags 12-18 months behind world prices, so farmers see little of the benefit of a price spike even as consumers pay more (Corporate Accountability Lab, 2025). Figure 1 illustrate the trend in cocoa futures prices from 2022 to 2025 (Cocoa Runners, 2024; Chocolate Affairs Magazine, 2025; Fell, 2026).

These pressures have renewed interest in producing cocoa-like ingredients without the cacao tree. Two distinct but frequently conflated approaches are now grouped under the popular label

of lab-grown chocolate. The first, cellular agriculture or plant cell culture, isolates living cells from cacao tissue and multiplies them in nutrient-rich liquid media inside bioreactors to yield cocoa biomass that is, in principle, bioidentical to field-grown cacao. The second, often called cocoa-free or precision-fermentation chocolate, uses no cacao-derived cells and instead rebuilds the taste, aroma, texture, and melting behaviour of chocolate from other feedstocks through fermentation, roasting, and flavour chemistry. The main subject of this review is plant cell culture, the approach best described as growing chocolate, set against the cocoa-free route as a competing and, in places, complementary path to the same market.

This review has three aims: to describe the biological and engineering basis of cell-cultured cocoa production; to document the state of industry activity, academic research, and regulatory review as of mid-2026; and to weigh, within the limits of the evidence, the technical obstacles and prospects of the technology, including its possible environmental benefits and its consequences for the millions of farmers who now depend on conventional cacao

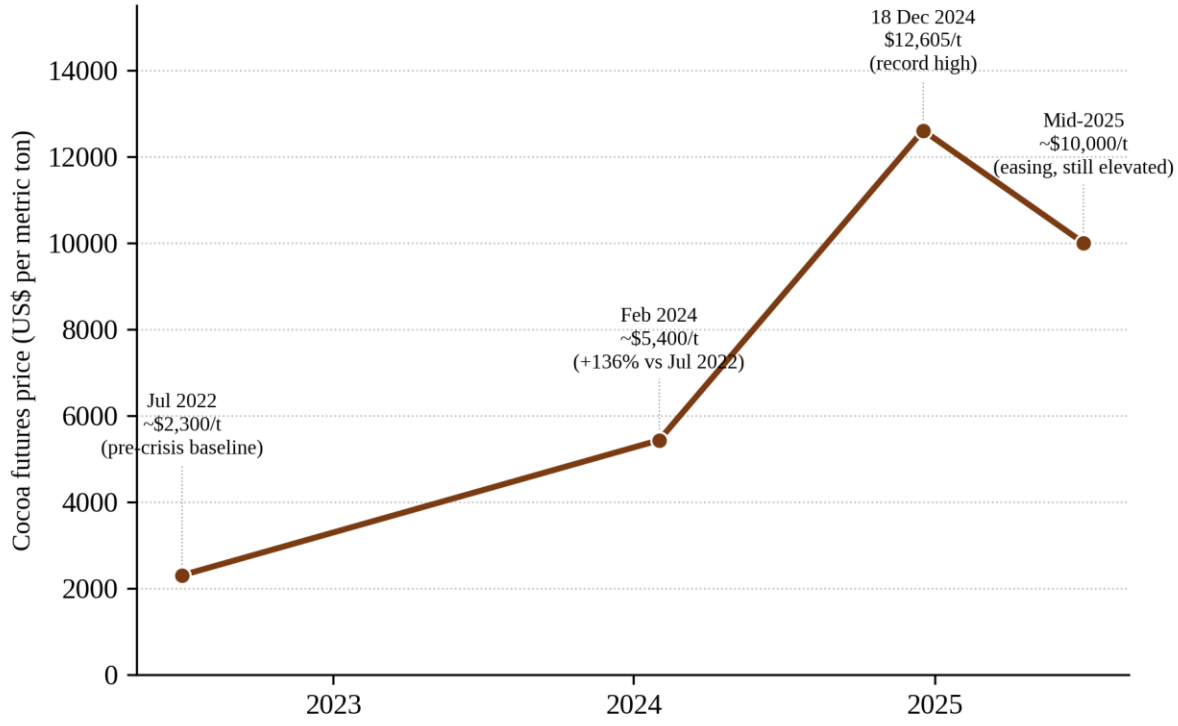


Figure 1: Illustrative trend in cocoa futures prices, 2022-2025, based on reported milestones (Cocoa Runners, 2024; Chocolate Affairs Magazine, 2025; Fell, 2026). Values between anchor points are interpolated for visualization and do not represent verified daily prices.

Climate vulnerability

Cacao is unusually sensitive to climate. It grows best within about 20 degrees of the equator in narrow bands of temperature and humidity, and West Africa now sees roughly 40 more days per year above 32 degrees C than in earlier decades, above which cacao growth suffers (Fell, 2026; Fletcher, 2024). A crop-modelling study of cocoa production under mid-century climate scenarios, together with modelling cited by UC Davis News, projects that as much as 50% of the cocoa-growing land in Cote d'Ivoire could become unsuitable by 2060 under continued warming (Fell, 2026; Asante *et al*., 2025). Heavy rainfall during Ghana's usually dry season has encouraged black pod disease, a fungal-like infection whose spread and yield damage across Ghanaian farms are recorded in the plant-pathology literature, and later drought has added further stress (Fell, 2026; Akrofi *et al*., 2015). Cacao swollen shoot virus has been especially damaging; epidemiological reviews report yield losses of up to 70% and, in severe cases, tree death within two to three years of infection (Fell, 2026; Ameyaw *et al*., 2024).

Deforestation and environmental footprint

Cocoa cultivation has also driven tropical deforestation. Forest clearance for cacao accounts for an estimated 70% of illegal deforestation in Cote d'Ivoire (Cocoa Runners, 2024), and the country has lost more than 85% of its forest cover since 1960, with cocoa expansion a leading cause (Mridul, 2024/2025). The downstream footprint is also large. Life-cycle assessments put greenhouse gas emissions for milk chocolate at roughly 4.2 kg CO2-equivalent per kilogram of product and about 1.6 kg CO2-eq/kg for extra-dark chocolate, with raw agricultural production responsible for most of the land use and marine eutrophication across the supply chain (Colmenares-Quintero *et al*., 2025; Bianchi *et al*., 2021). Water use varies widely by production system and place. Conventional Ecuadorian systems use roughly 0.305 cubic metres of water per kilogram of cocoa against about 0.009 cubic metres for organic systems, while Ghanaian production is penalised by high water use and Indonesian monoculture by heavy agrochemical use (Colmenares-Quintero *et al*., 2025). By some accounts a single bar of chocolate can require on the order of 1,700 litres of water across its supply chain, and among common foods only beef exceeds dark chocolate in carbon footprint (Mridul, 2024/2025).

Economic and social pressures

The economics of cacao farming worsen its environmental fragility. Only an estimated 16% of farmers in reporting companies' supply chains earn enough to meet basic needs (Corporate Accountability Lab, 2025). Because farmgate prices in the two main producing countries are set well behind world prices, farmers absorb the downside of volatility without much of its upside. Persistent poverty in turn drives more deforestation, as farmers clear extra land to make up for falling yields, and it is often named alongside price pressure as a driver of child-labour risk in the sector (Corporate Accountability Lab, 2025; Fell, 2026). These conditions have made the cocoa sector both a focus for sustainability-oriented food-technology investment and a serious humanitarian and ecological problem in its own right, independent of any technological fix.

High and volatile prices, ecological fragility, and widespread producer poverty are the conditions under which plant cell culture and cocoa-free chocolate have drawn venture investment, corporate partnerships, and academic research over the past three years.

TECHNOLOGICAL APPROACHES TO LAB-GROWN CHOCOLATE

Plant cell culure (cellular agriculture)

Plant cell suspension culture is a decades-old biotechnology platform, historically used to produce pharmaceutical compounds, pigments, and flavor molecules, that has more recently been applied to food ingredients including cacao, coffee, and various berries (Fell, 2026; Eibl *et al*., 2018; Ochoa-Villarreal *et al*., 2016). The underlying technology is well established in the peer-reviewed literature. Plant cell and tissue culture has been used commercially since the early 1980s to manufacture secondary metabolites such as ginseng saponins, shikonin, and other food- and cosmetic-grade compounds at bioreactor scale, and its extension toward mainstream food ingredients has been the subject of several academic reviews over the past decade (Eibl *et al*., 2018; Ochoa-Villarreal *et al*., 2016). The basic process begins with sampling tissue from a cacao plant selected for desirable organoleptic properties. Cells from that tissue are dedifferentiated, induced to revert to an unspecialized, rapidly dividing state, and then placed in liquid nutrient media containing sucrose as an energy source, mineral salts, vitamins, and plant growth-regulating hormones that maintain the cells in their proliferative state, a formulation whose basic composition traces back to the original plant tissue culture medium first described in the plant physiology literature (Fell, 2026; Cocoterra, 2024; Murashige & Skoog, 1962). Because the cells do not require light, photosynthesis, soil, or the structural tissues of a whole plant, they can be grown in the dark inside sterile, temperature-controlled bioreactors, and in principle can be propagated indefinitely from a single founder cell line (Fell, 2026; Eibl *et al*., 2018). Several companies report that cacao cells can reach harvestable biomass within three to four days under optimized conditions, compared with the roughly five-year maturation period and multi-month annual harvest cycle of a cacao tree (Mridul, 2024/2025). Cacao-specific feasibility for this approach has independent support in the plant-science literature. Peer-reviewed protocols have demonstrated the establishment of cacao embryogenic cell lines in liquid bioreactor media, with genotype-dependent growth kinetics characterized for several commercial cacao varieties, which gives an experimental footing to the premise that commercial developers now build on (Guillou *et al*., 2018).

Once harvested, the cell biomass is subjected to processing steps analogous to conventional cacao post-harvest handling (fermentation, drying, and roasting) intended to develop the volatile and non-volatile flavor compounds characteristic of chocolate (Cocoterra,

2024). This is a critical and still-developing step. Much of chocolate's characteristic flavor arises not from the raw bean but from microbial fermentation of bean pulp followed by Maillard browning and Strecker degradation reactions during roasting, which have been shown in controlled roasting studies to generate the high-molecular-weight melanoidins and pyrazine compounds responsible for cocoa's characteristic color and aroma (Oracz & Nebesny, 2019; Barišić *et al*., 2019), and the extent to which this chemistry can be faithfully reproduced starting from undifferentiated cell biomass rather than a fermented, fully developed bean is one of the field's central open questions (see the Technical and Scientific Challenges section).

Because plant cell bioreactor systems are chemically and mechanically simpler than the bioreactors used for cultivated (animal) meat or the fermentation tanks used for precision-fermentation proteins, industry participants argue that capital expenditure, media costs, and R&D costs for cacao cell culture are substantially lower than for other cellular agriculture categories, a claim advanced as the basis for eventual price competitiveness with conventional cocoa (Fortune, 2024). Figure 2 summarised the conceptual production pathway for cell-cultured cocoa and the scientific basis of each process that involve in cocoa-free chocolate production.

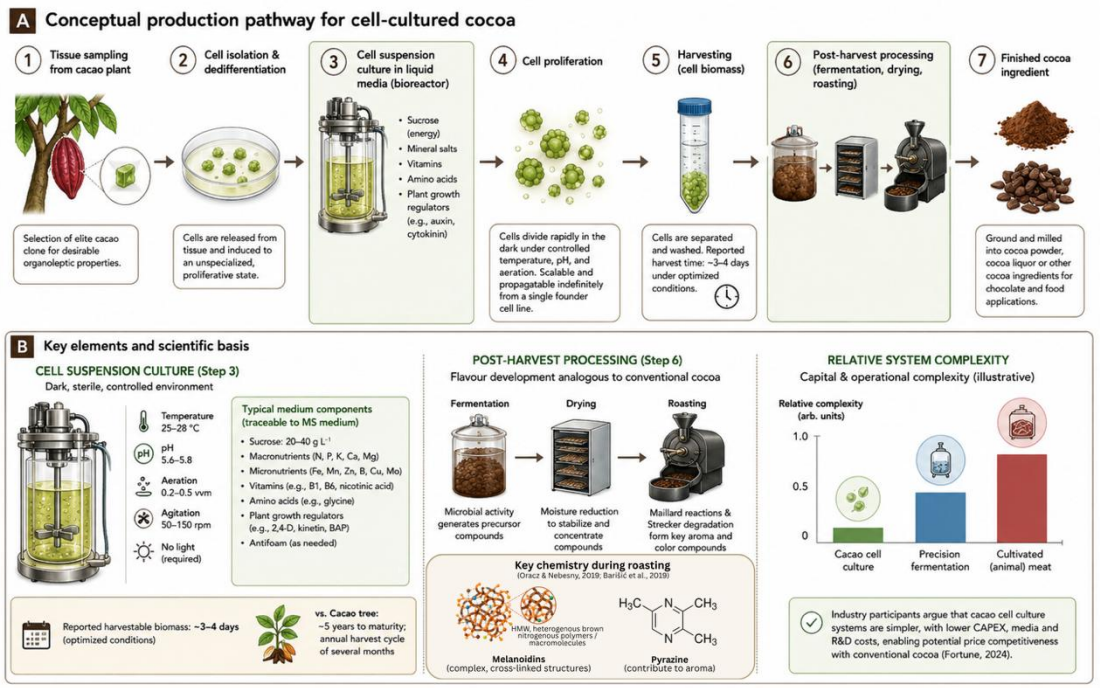


Figure 2: A) Conceptual production pathway for cell-cultured cocoa, from tissue sampling through to a finished cocoa ingredient. B) Key elements and scientific basis of lab-grown chocolate processing.

Cocoa-free and precision-fermentation alternatives

A second, in some respects more mature, category of chocolate reinvention uses no cacao cells at all. These cocoa-free products combine non-cacao feedstocks: oats and sunflower seeds fermented and roasted to mimic cocoa notes (Planet A Foods' ChoViva), grape-seed byproducts of winemaking with vegetable oils and sunflower protein (Voyage Foods), carob with grains and vegetable fats (Foreverland's Choruba), fava beans put through a bean-to-bar-style fermentation (Nukoko), or brewer's spent grain (Endless Food Co's THIC), with fermentation, roasting, and flavour engineering used to approach the taste, aroma, and mouthfeel of cocoa (Mridul, 2024/2025; Food Institute, 2026). Some of these firms, among them Planet A Foods, are also developing precision-fermented cocoa butter equivalents, in which single-cell microorganisms produce a fat with a triglyceride profile close to cocoa butter from agricultural sidestreams and feedstocks such as beet sugar (Mridul, 2024/2025).

These cocoa-free approaches are conceptually distinct from cell-cultured cocoa (Figure 3). They do not claim biological identity with cacao and are typically labeled and marketed as "alternatives" rather than as cocoa itself. However, they are commercially significant competitors and, in some cases, collaborators within the same broad effort to de-risk chocolate supply chains, and several, including Voyage Foods and Planet A Foods, have already achieved retail distribution at meaningful scale in Europe and, increasingly, the United States (Mridul, 2024/2025) as summarised in Table 1.

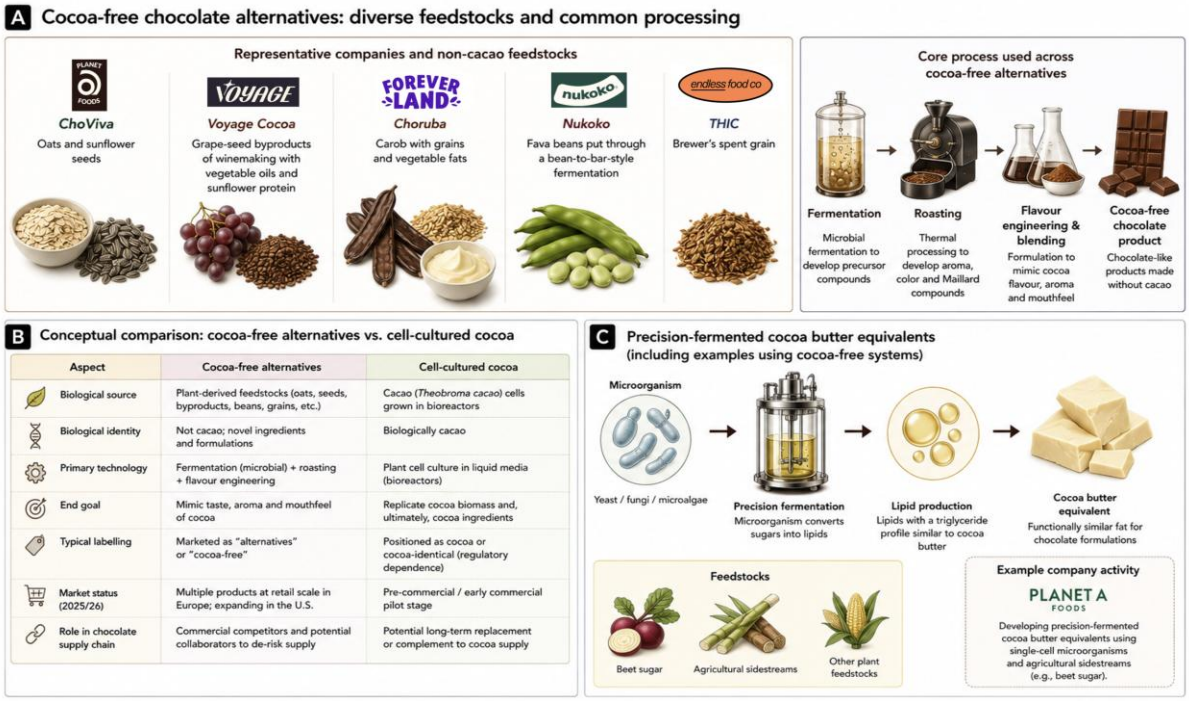


Figure 3: Technological approaches for cocoa-free and precision-fermentation-based chocolate production. (A) Cocoa-free chocolate production using alternative plant-derived feedstocks (e.g., oats, sunflower seeds, grape seeds, carob, fava beans, and brewer's spent grain) processed through fermentation, roasting, and flavour engineering to mimic cocoa characteristics. (B) Conceptual comparison between cocoa-free alternatives and cell-cultured cocoa, highlighting differences in biological origin, production technology, product identity, and commercial positioning. (C) Precision fermentation for the production of cocoa butter equivalents, in which microorganisms convert renewable feedstocks into lipids with cocoa butter-like triglyceride profiles for chocolate applications. Adapted from information synthesized from Mridul (2024/2025) and Food Institute (2026).

Table 1: Summary of the principal organizations active in this space as of mid-2026, their technological approach, and their reported stage of development.

Company / Institution	**Approach**	**Headquarters**	**Notable partners**	**Reported status (mid-2026)**
California Cultured	Cacao cell suspension culture (somatic embryos); scaling to reusable bioreactors up to 1,600 L	West Sacramento, USA	Puratos (Sparkalis), Meiji, UC Davis	GRAS filed with FDA; Puratos launch targeted late 2026; commercial powder targeted early 2027
Celleste Bio	Cell suspension culture for cocoa butter	Misgav, Israel	Mondelez International	Cocoa-butter chocolate prototypes announced Apr. 2026; commercial powder targeted early 2027

Company / Institution	Approach	Headquarters	Notable partners	Reported status (mid-2026)
Kokomodo	Cellular agriculture; multi-genotype cacao cell library; 3D cell-expansion platform (via Pluri)	Rehovot, Israel	The Kitchen FoodTech Hub, Plantae Bioscience, Pluri	US GRAS filing planned 2026
Food Brewer	Plant cell lines for cacao and coffee with AI-based growth monitoring	Zurich, Switzerland	Fruitful AI, Steinecker, Felchlin	Product testing under way; regulatory approval pending
Barry Callebaut / ZHAW	Academic-industry exploration of cocoa cell culture	Zurich, Switzerland	Zurich University of Applied Sciences	Early-stage exploratory partnership (2025)
UC Davis	Bioreactor and process-engineering research supporting cell-cultured cocoa	Davis, USA	California Cultured; funded by NSF, BioMADE	Ongoing bioreactor optimization and sensory/nutritional research
Voyage Foods	Cocoa-free chocolate (grape seed, sunflower protein, RSPO palm oil, shea)	Oakland, USA	Cargill, USDA	Commercial B2B products; large-scale Ohio factory under construction
Planet A Foods	Cocoa-free chocolate (oats, sunflower seeds, shea) plus precision-fermented cocoa-butter analogue	Planegg, Germany	Lindt, Nestle, Lambertz, Rewe, Edeka, Lidl, Aldi	ChoViva in 42,000+ EU stores; fermented butter analogue targeted 2026

CURRENT STATUS OF THE FIELD

Commercial momentum

Commercial activity in cell-cultured cocoa has increased since 2024. California Cultured, founded in 2020, opened a 12,000-square-foot production facility in West Sacramento and has secured a ten-year cocoa powder supply agreement with Japanese confectionery giant Meiji, alongside a strategic investment from Puratos's venture arm, Sparkalis (Mridul, 2024/2025; Fortune, 2024). In February 2026, Puratos announced plans to launch what it describes as the world's first professional chocolate product containing cultured cocoa, developed jointly with California Cultured and targeted for full US commercial availability by late 2026 (Food Institute, 2026). In April 2026, Israeli startup Celleste Bio, backed by Mondelez International, announced prototype milk chocolate bars made with cell-cultured cocoa butter, claiming that cells derived from a single cacao bean could theoretically generate up to a ton of cocoa butter per year, roughly equivalent to the annual output of a hectare of cacao trees. Both California Cultured and Celleste Bio have publicly targeted early 2027 for commercial cocoa powder production tied to specific purchase orders from chocolate manufacturers.

Beyond these two leading firms, Kokomodo (a subsidiary of Israeli biotechnology company Pluri) is developing a cacao cell library spanning multiple genotypes and cell lineages and plans a 2026 US regulatory filing; Food Brewer in Switzerland is applying artificial-intelligence-assisted growth monitoring to cacao and coffee cell lines in partnership with equipment maker Steinecker and Swiss chocolatier Felchlin; and Barry Callebaut, the world's largest B2B chocolate manufacturer, announced an exploratory partnership with the Zurich University of Applied Sciences in 2025 to evaluate cell-culture technology (Food Institute, 2026; Mridul, 2024/2025).

Academic research infrastructure

Alongside these commercial efforts, university research groups have begun to formalize plant cell culture as a distinct sub-field of cellular agriculture.

Researchers at the University of California, Davis are working with California Cultured, supported by grants from the US National Science Foundation and BioMADE, to optimize bioreactor geometry and operating conditions specifically for plant cell cultivation, with the explicit goal of reducing the cost of traditional bioreactor hardware, which is described as "prohibitively expensive" when adapted from pharmaceutical-scale equipment to food-scale production (Fell, 2026; Barzee *et al*., 2022). This program frames plant cell suspension culture as a potentially versatile production platform for a range of foods and food ingredients beyond cocoa, including coffee, berries, and walnut embryos, based on the same underlying biology of dedifferentiated plant cells grown in dark, sterile, sugar-fed liquid culture (Fell, 2026; Eibl *et al*., 2018).

So far, the peer-reviewed literature has concentrated on the microbiology and biochemistry of conventional cocoa fermentation rather than on cell-cultured cocoa, which is documented mainly through press releases, company statements, and university news rather than primary research articles. This fits the early stage of the field. Formal peer-reviewed work on the chemistry, safety, and sensory properties of cultured cocoa appears to be in preparation or under review at most of the companies and laboratories involved. The situation is not specific to cocoa. Broader reviews of cellular agriculture point to bioprocess cost, medium composition, and regulatory clarity as the bottlenecks common to cell-cultured foods, from cultivated meat to plant cell culture (Eibl *et al*., 2021; Barzee *et al*., 2022).

Regulatory pathways

In the United States, novel food ingredients derived from plant cell culture are generally reviewed under the FDA's Generally Recognized as Safe (GRAS) framework, which allows companies to self-affirm safety, optionally supported by a voluntary GRAS notification to the FDA seeking a "no questions" response. California Cultured has stated it is pursuing exactly this route and describes its submission as the first GRAS filing for a cocoa powder produced through plant cell culture (Mridul, 2024/2025). Kokomodo has indicated it plans to file a comparable US submission in 2026 and has explicitly cited the US GRAS pathway as simpler and faster than the European Union's approval process, leading it to prioritize a US launch (Mridul, 2024/2025).

The EU imposes a substantively different and generally more demanding framework. Under Regulation (EU) 2015/2283, any food or food ingredient not demonstrated to have significant consumption history within the EU before 1997 must undergo a pre-market "novel food" safety assessment conducted by the European Food Safety Authority (EFSA) before it may be marketed. There is a directly relevant regulatory precedent already established in this framework. EFSA has previously evaluated and approved apple fruit cell culture biomass, produced via essentially the same plant cell suspension technology now being applied to cacao, as a novel food, concluding that the biomass was safe under specified conditions of use (EFSA NDA Panel *et al*., 2023). The precedent points to a plausible but untested pathway for cell-cultured cocoa in Europe; no company reviewed here has completed an EU novel food submission for cacao cell culture as of mid-2026. Cocoa-free analogue products, by contrast, generally rely on ingredients already recognized in food use and therefore largely avoid novel food review, which has allowed companies like Planet A Foods and Voyage Foods to reach large-scale European and US retail distribution well ahead of any cell-cultured cocoa product.

Cost, scale, and production economics

Cost remains the central commercial variable. Industry participants uniformly describe current production costs for cell-cultured cocoa as higher than conventional cocoa, with cost competitiveness expected to depend on scale-up rather than any fundamental cost advantage inherent to the technology (Food Institute, 2026). California Cultured's transition from single-use to reusable plastic bioreactors, and its work with UC Davis on low-cost bioreactor geometries specifically engineered for food-grade plant cell cultivation, is explicitly framed as a strategy to close this cost gap (Fell, 2026; Food Institute, 2026). California Cultured has also emphasized that, relative to cultivated meat or precision-fermented proteins, plant cell culture requires comparatively simple, low-cost growth media and lower capital expenditure, which the company argues gives cacao cell culture a more direct path to price parity with commodity cocoa than other cellular agriculture categories have achieved (Fortune, 2024).

TECHNICAL AND SCIENTIFIC CHALLENGES

Flavor and aroma development

Reproducing chocolate flavour is the technical problem raised most often for cell-cultured cocoa. In conventional production the flavour is absent from the raw bean and develops over several days of spontaneous fermentation of the pulp-covered beans, during which yeasts, lactic acid bacteria, and acetic acid bacteria succeed one another and produce ethanol, organic acids, and a set of flavour precursors. Roasting then converts these precursors into the roasted, chocolatey aroma and taste through

Maillard and Strecker degradation reactions. This chemistry is well described in the peer-reviewed literature. Trials using defined microbial starter cocktails have measurably changed the flavour of the finished chocolate relative to spontaneous fermentation (Moreira *et al*., 2017), and a review of yeast starter cultures has set out the enzymatic and metabolic pathways, among them pectinolysis, citrate assimilation, and ethanol and ester production, that generate cocoa flavour precursors (Díaz-Muñoz & De Vuyst, 2022). Cell-cultured cacao biomass is not a fermented, ripened bean but undifferentiated tissue, so reproducing this precursor chemistry means either building a fermentation step for the harvested biomass that copies the microbial succession above, or inducing similar transformations by other means before roasting. UC Davis researchers and their industry partners list food-safe growth media, strain productivity, and the sensory and nutritional properties of cultured cells as unresolved research priorities (Fell, 2026).

Bioreactor engineering and scale-up economics

Plant cells behave differently from the microbial or animal cells used in other fermentation-based food technologies. They are larger, more shear-sensitive, tend to aggregate, and grow more slowly, which complicates the direct transfer of bioreactor designs from pharmaceutical or industrial biotechnology to food-scale cacao production (Eibl *et al*., 2018). California Cultured's demonstration of proof-of-concept cultivation in 1,600-liter bioreactors represents a meaningful scale-up milestone, but commentary from UC Davis researchers indicates that conventional bioreactor hardware remains prohibitively expensive for food-scale economics, motivating the development of purpose-built, lower-cost reactor geometries (Fell, 2026). A cross-category review of cell-cultivated food production similarly identifies bioreactor capital cost, sterility maintenance at scale, and the transition from batch to continuous or fed-batch operation as the shared engineering bottlenecks constraining commercialization across cultivated meat, microbial fermentation, and plant cell culture alike, rather than issues specific to any one product category (Barzee *et al*., 2022). Achieving the volumes needed to supply even a modest fraction of the roughly 4.5-5 million metric tons of cocoa beans processed globally each year would require bioreactor capacity, sterility management, and continuous-culture reliability well beyond what has been publicly demonstrated to date.

Nutritional and compositional equivalence

Conventional cocoa has a distinctive lipid profile along with flavanols, methylxanthines, and other bioactive compounds that matter both to the sensory qualities of chocolate and to its claimed health effects. The clinical side of this profile is well documented. A systematic review and meta-analysis of randomized controlled trials found that cocoa flavanol intake has measurable, favourable effects on cardiometabolic biomarkers, including lower blood pressure and better endothelial function (Lin *et al*., 2016); a cell-cultured product would have to match this compound profile to support similar claims. Whether cell-cultured cacao biomass, grown without the developmental and environmental signals of a whole plant, reproduces the profile at the same concentrations is an open question that current research programmes list as unresolved (Fell, 2026).

Substantiating food safety at novel-food standard

Even where cell-cultured biomass closely resembles conventional cocoa in composition, proving it to regulatory standard is slow and demanding, above all under the EU novel food framework, which requires detailed toxicological, allergenicity, and compositional dossiers. The EFSA assessment of apple cell culture biomass shows the kind of evidence a comparable cacao dossier would have to supply (EFSA NDA Panel *et al*., 2023).

Consumer perception as a non-technical but decisive barrier

Industry sources report real consumer skepticism. A flavour scientist interviewed by the Food Institute described the social-media response to coverage of cell-cultured chocolate as largely negative, with people calling the product artificial and worrying about more chemicals, though younger consumers were more open to the sustainability argument (Food Institute, 2026). The pattern matches the yuck factor and neophobia recorded in consumer research on cultivated meat, where acceptance rests mainly on perceived environmental and animal-welfare benefits but is held back by perceived unnaturalness, food-safety worries, and unfamiliarity with the cell-culture process (Bryant & Barnett, 2020). Cell-cultured cocoa shares the grown, not farmed framing, so similar barriers are likely, and success in the bioreactor will not by itself secure success on the shelf.

ENVIRONMENTAL AND SOCIOECONOMIC IMPLICATIONS

Potential environmental benefits

The main environmental argument for cell-cultured cocoa is that it could separate chocolate production from land-hungry, climate-exposed farming. Because the cells grow in sterile, climate-controlled bioreactors rather than fields, its supporters argue it could be produced without deforestation, without the water demand of field cultivation, and without

exposure to the pests, drought, and disease now threatening West African cacao (Fell, 2026; Fortune, 2024). No independent, peer-reviewed life-cycle assessment (LCA) of cell-cultured cocoa has yet been published, and the environmental claims from companies remain largely qualitative or unverified at commercial scale. The closest peer-reviewed evidence is cautionary. An LCA of two other food-grade plant cell cultures, tobacco BY-2 and cloudberry cell lines, found that electricity for bioreactor operation, not any farm input, drove 82-93% of several impact categories, and that the global warming potential of the fresh biomass resembled that of heated greenhouse produce rather than open-field crops; the same study found that better bioreactor operation could cut impacts by up to 47% (Kobayashi *et al*., 2022). This qualifies the simple no-farm-no-footprint argument. Whether cell-cultured cocoa gains a real environmental advantage over field-grown cacao will turn on the carbon intensity of the electricity that powers the plants, the carbon intensity of the sugar-based medium, and the degree of bioreactor optimization reached at scale, not on the absence of farmland alone. The cocoa-free analogues report firmer figures. Voyage Foods cites independent analysis putting the emissions of its grape-seed compound 81-84% below conventional chocolate, and Foreverland claims its carob-based Choruba uses about 90% less water and emits about 80% less greenhouse gas (Mridul, 2024/2025). The relative greenhouse gas impact of chocolate and chocolate-alternative categories was shown in Figure 4.

Implications for cacao-growing economies

The socioeconomic effects of a shift to lab-grown chocolate are more disputed than the environmental case. Tens of millions of people across West Africa, Latin America, and Southeast Asia depend directly or indirectly on cacao farming for their livelihoods. If chocolate manufacturers move even part of their demand from field-grown cacao to bioreactor-produced biomass, smallholders who mostly already earn too little to meet basic needs (Corporate Accountability Lab, 2025) could lose market. None of the literature reviewed here quantifies this displacement risk, and companies have generally presented their technology as a supplement to traditional cocoa rather than a replacement (Food Institute, 2026). Whether that holds as the technology scales, or whether cost pressure eventually pushes manufacturers toward substitution, is an important open question and a candidate for future interdisciplinary research.

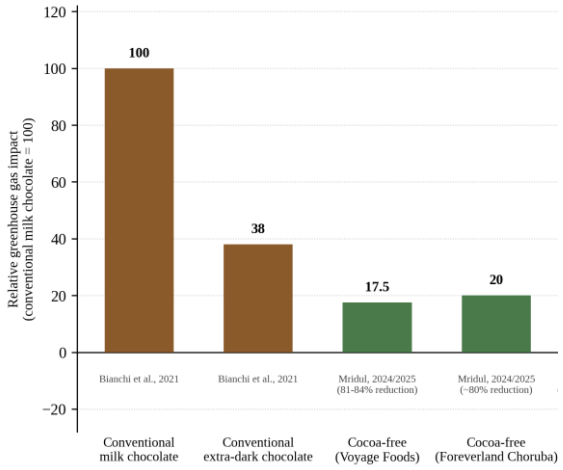


Figure 4: Relative greenhouse gas impact of chocolate and chocolate-alternative categories, indexed to conventional milk chocolate = 100.

CONSUMER ACCEPTANCE AND MARKET OUTLOOK

Market analysts and food-industry commentators broadly agree that the technology is further along than consumer readiness (Food Institute, 2026). Industry opinion points to a generational split, with younger consumers more open to sustainability-driven reformulation and older consumers more resistant to processed or artificial-seeming ingredients, much as in the cultivated meat sector. Labelling and framing will probably decide the outcome. A product sold as cultured cocoa invites comparison with cultivated meat and its controversies, whereas one sold on sustainability and flavour parity may meet a warmer response, especially if it appears first in professional and food-service channels rather than on retail shelves. Almost every company profiled here follows the same commercial pattern: first launches aimed at professional and B2B buyers rather than mass-market shelves, which reads as industry treating consumer acceptance as a slow, trust-building process.

FUTURE PROSPECTS

Near-term commercialization timeline

Public statements from the companies point to a rough shared timeline. The years 2025 and 2026 cover pilot-scale validation, regulatory filing, and B2B product development; late 2026 is the target for the first limited commercial launches in professional and food-service channels; and early 2027 is the date several companies have set for commercial-volume

cocoa powder tied to specific purchase orders from established manufacturers (Figure 5). These are company targets, not independently verified milestones, and given the technical uncertainties above, some slippage is likely, as it has been in other cellular agriculture categories such as cultivated meat.

Convergence and hybridization

A plausible medium-term trajectory, suggested by the current pattern of industry partnerships, is convergence rather than outright substitution. Cell-cultured cocoa components, such as cocoa butter, which is more chemically tractable to reproduce than the full flavor complexity of cocoa solids, may reach cost and quality parity with conventional cocoa before whole cocoa powder does, leading to blended products that combine cell-cultured cocoa butter with conventionally sourced, fairly traded cocoa solids. Likewise, the parallel maturation of cocoa-free analogues suggests a future confectionery market segmented by ingredient technology and price point, rather than a single "winning" replacement for conventional cocoa.

Research priorities

Four research priorities follow from the gaps above: peer-reviewed, independently verified life-cycle assessments of commercial-scale cell-cultured cocoa; systematic sensory and biochemical comparison of cell-cultured biomass with conventionally fermented cacao in the peer-reviewed literature; socioeconomic modelling of how cell-cultured cocoa adoption affects smallholder cacao economies; and continued bioreactor engineering to lower the capital and operating costs of food-grade plant cell culture.

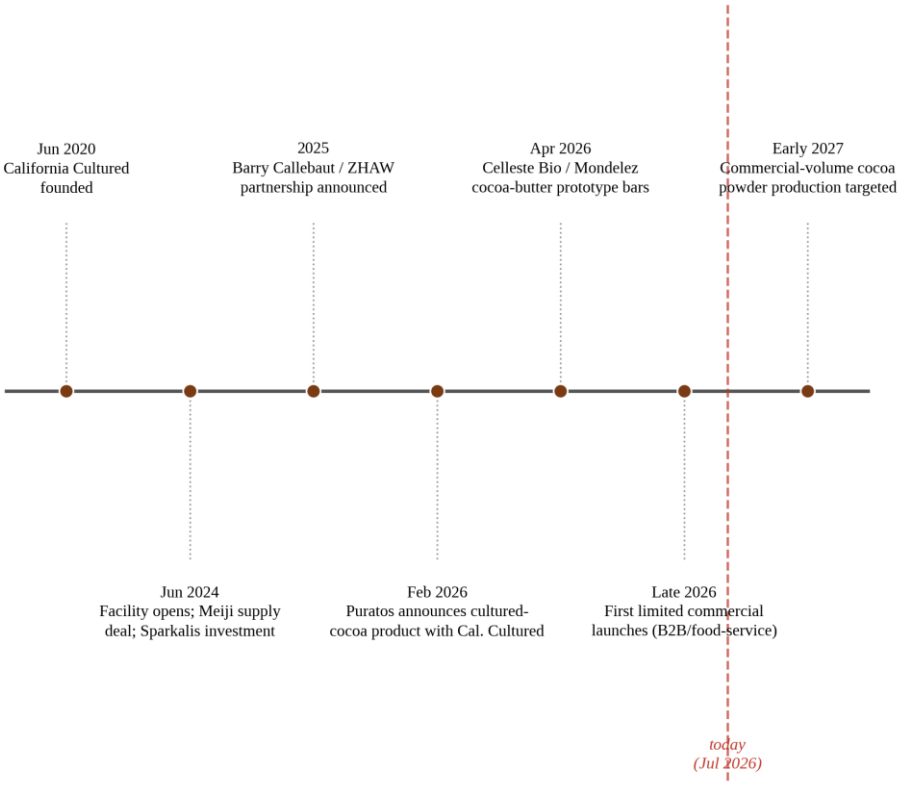


Figure 5: Reported and targeted milestones in cell-cultured cocoa commercialization, 2020-2027. Dates after mid-2026 reflect company-stated targets rather than confirmed outcomes (Food Institute, 2026; Fell, 2026).

CONCLUSION

Lab-grown chocolate, taken to cover both cell-cultured cocoa and cocoa-free fermentation analogues, has moved in about three years from a concept to a field with pilot-scale production, named partners among major chocolate manufacturers, filed regulatory submissions, and stated commercialization dates. Much of this has been driven by the crisis in conventional cocoa supply, which has made the traditional supply chain look fragile to the manufacturers that depend on it. At the

same time, the scientific literature specific to cell-cultured cocoa is still thin next to the volume of industry announcements and press coverage. Questions about flavour precursor development, nutritional equivalence, bioreactor economics at commercial scale, and life-cycle environmental performance remain open. A regulatory route exists, with the EU's earlier approval of plant cell culture biomass from apple as a workable precedent, but no cacao-specific approval has been finalized in the United States or the European Union as of mid-2026. Consumer acceptance is uncertain and is being handled cautiously through B2B rather than retail launches. The most likely near-term outcome is partial, incremental commercialization over the next one to three years, starting with cocoa butter and professional confectionery rather than mass-market bars. What the technology will mean over the longer term for consumers and for cacao-growing economies is still unsettled and will need closer, peer-reviewed study.

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