

## Lessons in Tropical Biomass: Exploring the Potential of Cacao Fruits

**Abstract.** While cacao is a cornerstone of Colombian agriculture, the traditional linear production model suffers from a stark inefficiency: only 8% to 10% of the fruit's total biomass is used for chocolate beans, leaving 90% to 92% to be discarded as environmental waste. This plenary lecture presents the results of over a decade of intensive laboratory research aimed at bridging the "circularity gap" in cacao fruit biomass by transforming biomass residues into a portfolio of high-value bioproducts through a systematic biorefinery approach.

Our research first established a foundational understanding of the cacao fruit's inherent complexity by mapping the mass balance and compositional dynamics of its four primary streams: the husk (CH), beans (CB), placenta (CP), and cacao mucilage exudate (CME). Crucially, our year-long longitudinal study of the CCN51 clone revealed that tropical biomass composition is not static; it is highly time-dependent and significantly correlated with rainfall patterns. For instance, structural biopolymers in the husk and the total carbohydrate content in CME (ranging from 10% to 29%) vary across harvest cycles. These findings emphasize the need for seasonal tracking as a prerequisite for optimizing downstream industrial conversion efficiency.

A central pillar of our work has been the valorization of CME, a nutrient-rich effluent traditionally lost during fermentation. We have successfully scaled cacao syrup production from CME, optimizing processing conditions to yield a sustainable, natural sweetener. Furthermore, our laboratory pioneered the use of CME as a culture medium for the biotechnological biosynthesis of bacterial cellulose (BC) and polyhydroxyalkanoates (PHAs). Utilizing the *Gluconacetobacter xylinus* strain and a wild-type *Bacillus megaterium* strain, we scaled these bioprocesses to 50 L reactors, achieving high yields of medical-grade cellulose and biodegradable thermoplastics.

Building on these biopolymers, we highlight the development of advanced functional materials, including biocomposite films for food packaging that integrate amidated nanocellulose and PHAs to enhance moisture resistance and mechanical integrity. When coupled with the extraction of natural pigments from the husk epicarp and phospholipids from the beans, these innovations provide a robust scientific framework for a comprehensive cacao-based biorefinery. This integrated model offers a dual solution: mitigating the environmental footprint of cacao production while significantly bolstering the economic resilience of smallholder farmers in tropical regions.

**Keywords:** Cacao mucilage exudate, Circular bioeconomy, Bacterial cellulose, Polyhydroxyalkanoates, Lignocellulosic biomass, Colombia.