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Circular silk protein technologies promote plant growth and reduce food waste

By **Benedetto Marelli**

In the 20th century, new material-based technologies have positively impacted many aspects of human life, including health management, communication, education, and transport, as well as improved our access to energy, water, and food. Continued technological advancement to improve quality of life must now consider sustainability alongside mitigation and adaptation to climate change (*1*). Scientists and engineers are looking to living systems to learn how to translate sustainability principles into material design. Soft matter and structural biopolymers (e.g., DNA, proteins) are being used to design technologies that address unmet challenges in the health, energy, food and education sectors . These natural polymers are biomaterials which can be extracted in high volumes and low cost from byproducts of food and textile industries and upscaled into advanced materials (**Fig.1**a).

There is wide interest in the development of biomaterials, but their application in agro-food systems (i.e., all actors and activities involved in food production, distribution, regulation, and consumption) has lagged. Agro-food systems' infrastructure is responsible for more than 25% of anthropogenic greenhouse gas (GHG) emissions. These systems face pressure to support an increasing world population and to simultaneously minimize inputs (e.g., water, fertilizers, pesticides) and mitigate environmental impact. For the first time in history, the availability of arable land has plateaued, and crop yields are threatened by soil salinity and water scarcity–stressors exacerbated by climate change. Food security and food waste are twin crises; more than 800 million people are undernourished and 30% of food is lost or wasted from farm to fork. Food waste could potentially feed 1.6 billion people, instead it is responsible for 25% of global freshwater consumption and when considered en masse is the third largest producer of GHGs after China and the U.S. (*2, 3*). New technologies that are economically sustainable, scalable, and rapidly deployable to market are needed to address these challenges. These innovations must also meet stringent requirements for safety and biodegradability. Consumers' environmental responsibility is increasing and new laws limiting materials' environmental impact are on the horizon (e.g., the European Union ban on microplastics starting in 2025 (*4*)).

An opportunity lies for biomaterials to address these challenges in the agro-food industry. Our laboratory strives to reinvent silk as an advanced material to extend food shelf-life, boost crop production, and precisely deliver payloads in plants (*5-7*). Silk is an abundant, natural fiber produced by *Bombyx mori* caterpillars to make their cocoons. An edible, non-toxic protein, silk fibroin, can be extracted at low cost from byproducts of the textile industry (*8*). This protein is well-known for its mechanical strength, but its structural polymorphism (i.e., ability to fold in stable configurations ranging from a random coil to a β-sheet) is ideal for applications as a technical material. Silk fibroin's polymorphism enables its low-energy, water-based regeneration in water-soluble or water-insoluble materials, dependent on molecular structure and allows for nanomanufacturing in numerous material formats (*5, 8, 9*).

Our laboratory has investigated the self-assembly of regenerated silk fibroin in transparent coatings that can adhere to three-dimensional substrates via spray drying or dip-coating; retrofitting tools commonly used in the agro-food industry (*10, 11,12*). Modulation of polymorphism in silk coatings provides extraordinary barrier properties to water and oxygen as well as resistance to microbial spoilage and contamination. Payloads such as bacteria can be encapsulated and preserved in these silk coatings, and composite materials can be easily manufactured to further tailor coating properties. In the past few years, research I have contributed to has led to the spin out of technologies that use silk-based materials to enhance food security (**Fig.1** b,c).

In one example, safe-to-eat food coatings that extend the shelf life of perishable foods were developed (*11*). This edible silk coating can be applied to numerous types of foods, including produce, meats, fish, and consumer packaged goods. The coating is safe to eat (13) and decreases evaporation and oxidative stress and may contribute to the reduction of natural microbial spoilage. Mori (formerly Cambridge Crops, Inc.) is a 2021 World Economic Forum Technology Pioneer and utilizes some of the intellectual property (IP) that was developed alongside the initial research. Since its founding, Mori has raised upwards of $88 million and currently employs over 55 people in offices in Boston; Washington, DC; Salinas; and Mexico City. The food coating, considered a Non-Novel Food by Health Canada and other countries around the globe based on its historical worldwide consumption, is considered Generally Recognized as Safe in the US. Mori intends to continue to use this technology to extend shelf life and build a more resilient food supply.

In addition, our laboratory has also developed a silk-based seed coating technology for the delivery of plant growth promoting rhizobacteria (PGPRs). PGPRs boost plant health and crop yield by increasing availability of macronutrients, decreasing the use of synthetic fertilizers and pesticides, and mitigating abiotic stressors (*14*). Their use is frequently hindered by limited viability outside the soil and during desiccation. Using a combination of rational design and bioinspiration, silk and polysaccharides are combined to adhere to a seed surface, encapsulate and preserve bacteria in a dry state, and modulate their delivery and growth in the spermosphere (*15*). In field tests, conducted at an experimental farm in Ben Guerir, Morocco in collaboration with UM6P, PGPRs delivery via seed coatings boosted growth when plants were grown in saline soil and water stress conditions (*16*). The IP that protects this innovation may further help to establish a pattern towards its commercialization, having a positive impact on our society by mitigating climate and food crises.

Together, these technologies open the door to the application of biomaterials to boost food security and enhance agro-food resilience. We are bringing innovation to a field that needs creative solutions to enhance food production while minimizing inputs and mitigating environmental impacts.

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Figure (a) The Marelli Laboratory's longterm research mission flows into its general process to engineer structural proteins in advanced biomaterials. New discoveries in biomaterials science spur the translation of new solutions in agro-food systems. Examples of which are the use of silk fibroin-based technology as an edible food coating (b) to extend perishable produce shelf-life in kale and as a seed coating (c) to deliver biofertilizers which boost germination and mitigate soil salinity.

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