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The future of food colloids: Next-generation nanoparticle delivery systems

David Julian McClements

Department of Food Science, University of Massachusetts Amherst, Amherst, MA 01003, USA

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ABSTRACT

The area of food colloids is rapidly evolving. Food researchers are continuing to use theoretical, modeling, and experimental approaches to understand colloidal phenomena in foods and in the gastrointestinal tract, as well as to use colloid science to design foods with novel or improved functional attributes. In this article, a brief survey of potential topics of future study in food colloids is given, including the application of colloid science in improving food security, enhancing human health, and ensuring food quality and safety. Special emphasis is given to the development of next-generation delivery systems, such as mixed nanoparticle systems, nanoclusters, Trojan-horse nanoparticles, and environmentally responsive nanoparticles.

1. Introduction

It is difficult to accurately predict the future of any scientific discipline. If one looked at the field of food colloids when I started working in this area in the late 1980's it would have been difficult to predict the research areas that currently dominate the field, such as understanding the colloidal basis of food digestion and the development of structured delivery systems to control the gastrointestinal fate of nutrients and nutraceuticals. In those days, a much greater emphasis was given to understanding the various kinds of colloidal and interfacial phenomena that occurred within foods, and in relating colloidal phenomena to the bulk physicochemical properties of foods, particularly stability and rheology. The discipline has evolved considerably since then, with a much stronger emphasis on utilizing colloidal principles to rationally design new structures and functionalities in foods, and with a greater interest in understanding the colloidal phenomena occurring within the human body after a food has been ingested.

In some respects, the future of food colloids will look similar to the past and present. Many foods are highly complex materials that contain biopolymers and colloidal particles, and so it will continue to be important to use colloidal theories and techniques to understand, predict, and manipulate their behavior. Thus, many current areas of research will simply broaden and deepen as a wider range of materials is studied using a greater number of analytical approaches.

In other respects, the future of food colloids may look very different from the current discipline. It is likely that new topics of study will be identified and pursued, and that the introduction of novel analytical and computational tools will open up new areas of knowledge to be explored. Indeed, the problems that can be studied in a particular scientific discipline are often limited by the availability of suitable analytical tools to provide information about them.

In this article, I will first outline potential new areas of research in food colloids that are either driven by important societal problems that need to be addressed or by the introduction of new research tools. I will then focus on a particular area that is likely to rapidly expand in the near future: next-generation nanoparticle delivery systems.

2. Origin of new research areas: problem driven

New topics of research are likely to come from a number of directions. A great deal of science and technology is motivated by practical problems that need to be solved in the real world. Much of current research in colloid science is focused on the gastrointestinal fate of foods because of the greater appreciation of the close link between human diet and health, and the possibility of manipulating food composition and structure to improve human health and wellbeing through dietary interventions [1,2•]. Overconsumption of certain types of food components is leading to a variety of chronic diseases that adversely affect human well-being and that cost society considerable amounts of money in lost productivity and increased health care costs, *e.g.*, heart disease, obesity, diabetes, hypertension, and cancer [3–6]. Conversely, fortification of foods with other types of food components (nutraceuticals) may be able to inhibit or prevent chronic diseases [7–9]. Consequently, a great deal of current research in food colloids is focusing on using colloid and interface science to structure foods so as to improve their

E-mail addresses: mcclements@foodsci.umass.edu, liuchengmei@aliyun.com.

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nutritional profiles and alter their gastrointestinal fate [1,10,11•,12••,13]. In the future, colloid science may also be useful for tackling other existing or emerging societal challenges. A number of potential areas of focus are outlined in this section.

2.1. Food processing and sustainability

The continued growth of the human population means that an increasing amount of food will be required to provide a nutritious, healthy, and sustainable diet for all [14,15]. Humans will need to generate more food, and to utilize and distribute it more wisely. The principles and tools of colloid science may play an important role in developing a more efficient and sustainable food supply. Colloid science may improve the processes used to isolate, purify, and process foods and food ingredients so as to make them more efficient and sustainable. For example, waste streams from food processing plants may be converted into valuable ingredients that can be used for food or non-food applications, such as emulsifiers, thickening agents, gelling agents, foaming agents, or nutraceuticals [16,17]. Colloid science may also be useful for optimizing the efficiency of various processing operations, such as filtration, centrifugation, and thermal processing [18]. For example, an understanding of the attractive and repulsive interactions between colloidal particles can be used to promote or prevent their aggregation, which may help to separate them or keep them in suspension. Similarly, an understanding of the factors that impact the coalescence of oil droplets can be utilized to improve the separation of bioactive lipids (such as ω-3 oils) from natural and sustainable sources, such as the oil bodies in algae and plant seeds. Colloid science may also be useful for developing delivery systems that can increase the effectiveness and reduce the environmental impact of antimicrobials, pesticides, herbicides, *etc*. For example, nanoemulsion-based delivery systems are being developed to improve the efficacy of natural antimicrobial agents, such as essential oils [19–23].

2.2. Diet and health

Until fairly recently the majority of the research in food colloids was focused on understanding and controlling the processes that occur within foods themselves. For instance, a great deal of research was carried out on understanding the factors that influence the stability or rheology of oil-in-water emulsions. Recently, there has been an increasing interest in understanding the colloidal and interfacial processes that occur within the gastrointestinal tract (GIT) after the food is ingested [1,2•,12••,24–26]. For example, the influence of the composition and structure of emulsions on their gastrointestinal fate has been an area that has been the focus of a large research effort in recent years [2•,10]. In the future, food scientists may also be interested in controlling the colloidal and interfacial processes that occur within the systemic circulation and specific tissues after a digested food has been absorbed by the human body. This knowledge may lead to new approaches for fighting cancer, coronary heart disease, or other chronic diseases [27••]. For example, a food emulsion may be designed on the nanoscale to breakdown in the GIT and form specific nanostructures (mixed micelles and vesicles) that promote the absorption of beneficial nutraceuticals or nutrients. At the same time, the initial food emulsion could also be designed so that it is processed within the epithelium cells so as to form chylomicrons with specific dimensions and compositions. After being released into the systemic circulation these natural nanoparticles may be preferentially adsorbed by tumors, thereby enabling the delivery of anticancer nutraceutical components to the site of action more effectively. Thus, a highly integrated colloidal approach could be used to design the behavior of foods from before, during, and after ingestion [27••].

There has been a lot of interest in utilizing both organic and inorganic nanoparticles in foods to improve their safety, quality, or nutritional value [28,29]. However, the incorporation of these nanoparticles may alter the gastrointestinal fate and therefore toxicity of foods. Consequently, it is important to understand how both organic and inorganic food-grade nanoparticles behave in the human body [10,30••]. Nanoparticles (1 to 100 nm) are really a special class of colloidal particles (1 to 1000 nm) and therefore the principles and techniques of colloid science will prove especially important for understanding their biological fate.

The human microbiome is known to play a major role in determining human health and wellbeing, and can be manipulated through diet [31,32]. As knowledge about the specific components within the human diet that lead to a healthy microbiome advance, it may be possible to use colloid science to design foods that deliver an optimized balance of nutrients to the gut microbiota. Alternatively, it may be possible to use food-grade colloidal particles as diagnostic tools to provide information about the status of the human microbiome. For example, a food could contain colloidal particles that produce measurable signals when they encounter certain conditions in the human colon associated with disease states, *e.g.*, specific metabolites produced by gut bacteria. For instance, the colloidal particles may cause a change in the color of the feces, which informs a person to go for a more detailed health check.

2.3. Food diagnostics

There have been rapid advances in the development of sensors to monitor the safety and quality of food products, and then report the information obtained to food manufacturers or consumers, *e.g.*, smart labels, microfluidic chips, paper assays, or in-product probes [33–39]. These sensors may report if a product has received temperature abuse, if it has been contaminated with spoilage or pathogenic microorganisms, if it has reached the end of its shelf life, or if it contains undesirable levels of toxins, pesticides, herbicides, or hormones. Colloid science may play an important role in the development of many of these sensors. For example, colloidal particles could contain sensors that generate a measureable change when they are exposed to specific temperature, light, pH, enzyme, or chemical environments, such as a color change. These sensors could be contained within the interior of the colloidal particle or they may be adsorbed to the particle surface. Alternatively, the colloidal particles may simply aggregate and become turbid when a specific change in environment occurs. Colloidal sensors could be part of food packaging or they could be added into the food itself (provided that they are known to be safe and do not affect food quality).

2.4. Natural foods

There is an increasing interest by many consumers in consuming natural or minimally processed foods because they are perceived to be healthier and more environmentally friendly [40]. Colloid science may prove to be useful for understanding how these foods behave during processing, transport, utilization, and consumption, which may lead to products with better quality attributes or nutritional properties. In particular, there is a great interest in replacing synthetic food ingredients (such as colorants, flavorings, preservatives, emulsifiers, foaming agents, thickeners, and gelling agents) with more natural alternatives, *e.g.*, natural pigments, oils, proteins, polysaccharides, or phospholipids. For instance, there has been a push towards identifying, isolating, and characterizing natural emulsifiers to replace synthetic ones [41–44•,45•]. Another area of interest has been in the identification of specific colloidal structures within natural materials (such as fruits and vegetables) that may be utilized as natural delivery systems for bioactive agents. For example, oil bodies are designed by nature to store lipids and protect them from environmental stresses (until they are needed by the plant, animal, or microbe as an energy source to grow), and so it may be useful to design processing operations that leave these structures intact so that they can be utilized as food ingredients [46–49•,50]. Oil bodies consist of lipid droplets containing hydrophobic bioactives and triglycerides that are naturally coated by a layer of phospholipids and proteins.