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Review

Spray drying of probiotics and other food-grade bacteria: A review

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ABSTRACT

Background: Probiotic and starter bacteria are generally dried to produce easy-to-use ingredients that are stable and flexible for applications in the food, feed and pharmaceutical industry. The overall demand for dried probiotic bacteria has increased in the context of a rapidly growing market, evidencing the need for their larger scale production.
Scope and approach: The spray-drying of bacteria enables a larger production scale than the freeze-drying currently used; energy costs are lower and the process is sustainable. This is also a promising way to microencapsulate bacteria within various protective matrices to ensure their improved resistance during storage, technological processes and digestive stresses.
Key findings and conclusions: This review highlights some key strategies to improve the viability and efficacy of probiotics spray-drying, such as the enhancement of bacterial resistance, improved protection of the drying medium and optimization of the drying process. It also focuses on factors during the pre- and post-drying stages which may influence the quality and efficacy of spray-dried probiotic powders.

1. Introduction

In recent years, increasing numbers of bacteria have been investigated for their probiotic potential, as they confer health benefits on the host when administered live and in appropriate quantities. The beneficial effects of probiotics depend on the specific strain or specie, the dose and viability of the bacteria ingested (Hill et al., 2014). The International Dairy Federation (IDF) recommends a minimum of 10^7 live probiotic bacterial cells per gram or milliliter of product at the time of consumption (Corona-Hernandez et al., 2013). Therefore, maintaining adequate levels of viable cells and ensuring their properties throughout shelf-life is a prerequisite for their further use, e.g. when incorporated in food products and during the digestion process.

Drying is a widely-used process for food preservation, ensuring a stable and extended shelf-life, reducing transportation costs and facilitating trade. Freeze-drying remains the preferred technique to preserve probiotic bacteria; but it is a time-consuming and expensive process (Table 1). Among the drying techniques that are possible, spray-drying is one of the most predominant in the dairy industry (Schuck et al., 2016). It consists in spraying the liquid feed in fine droplets (10–150 μm) that are directed into a flow of hot and dry air (usually 150 °C–250 °C). The increase in the air-liquid interface area subsequent to spraying dramatically increases the drying kinetics, and it is generally admitted that drying occurs within a few seconds. When compared to freeze-drying, spray-drying represents a lower specific energy cost and higher productivity (Table 1). There remain challenges associated with the use of spray-drying to produce viable cultures, especially with “sensitive” probiotic strains (Broeckx, Vandenheuvel, Claes, Lebeer, & Kiekens, 2016; Fu & Chen, 2011; Peighambardoust, Golshan Tafti, & Hesari, 2011).

This review offers an update of the state-of-the-art on the adaptive response of probiotic bacteria to several stresses related to spray-drying conditions (Fig. 1). We also review recent advances in the preparation and spray-drying conditions for probiotic culture that have been shown to be protective or have a positive impact on probiotic viability.

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Table 1
General production pattern and specific energy consumption of commonly used concentration and drying processes. Data from Bimbenet, Schuck, Roignant, Brulé, and Méjean (2002) and Schuck et al. (2015).

Processes	Production pattern		Specific energy consumption (kJ.kg^{-1} water)	Productivity (ton.year^{-1})	Advantages	Limits
Membrane separation	Liquid → Concentrate	Batch Continuous	40	n.a.	Low temperature and energy cost	Fouling, non-specificity of the cut-off, cost of the replacement of membranes
Spray- drying	Liquid → Solid	Continuous	5300	~50000[a]	Low heat treatment and residence time	High investments
Freeze-drying	Liquid → Solid	Batch	18,000	~10000[a]	Very low heat treatment, production of porosity, improvement of rehydration	High residence time (24–48 h)
Fluidized-bed drying	Solid → Solid	Continuous	11,400	n.a.	Low heat treatment, production of powder below T_g	Very high specific energy consumption, high residence time and investments

n.a.: not available.
[a] An approximate value for a large scale dryer from personal communication (The productivity actually depends on equipment, production scale and market demand).

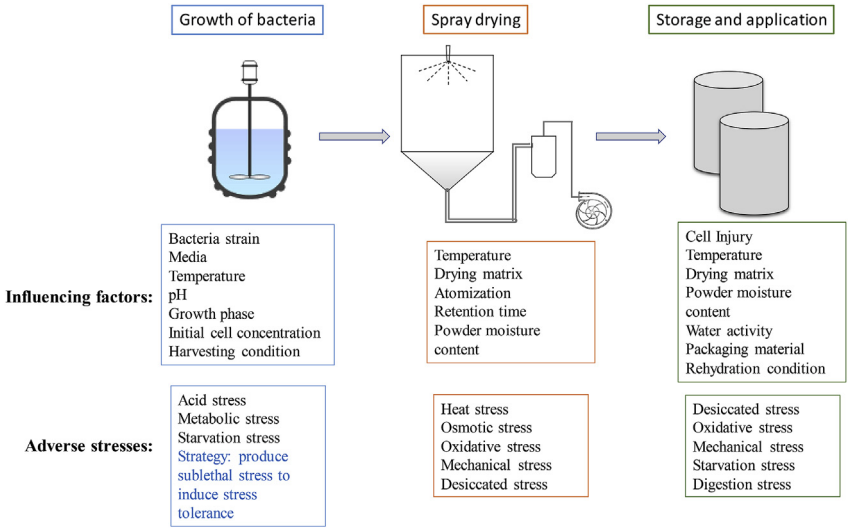

Fig. 1. The most influential factors and adverse stresses experienced during the growth, spray-drying, storage and application of probiotics.

2. Pre-drying stage

2.1. Selection of bacterial strains

To date, most efforts have focused on the drying of *Lactobacillus*, *Lactococcus* and various *Bifidobacteria* species. These probiotic bacteria generally do not survive well after spray-drying because of the harsh conditions which prevail during the process (Table 2). The resistance characteristics of a bacterial strain should thus constitute an important criterion when selecting probiotic bacteria, in order to improve the final probiotic viability of the spray-dried powders.

Heat, osmotic, oxidative and desiccation stresses are usually considered to be the main mechanisms which cause the inactivation of bacteria during and after spray-drying (Santivarangkna, Kulozik, & Foerst, 2008). It has been shown that different bacterial species, or even strains, may display variable tolerance towards such stresses.

By comparison with *Lactobacillus*, *Lactococcus* and *Bifidobacteria*, *Propionibacteria*, whose probiotic properties were reviewed by Cousin, Mater, Foligné, and Jan (2010), usually display higher tolerance due to their greater abilities for environmental adaptation, either through their metabolism or a multi-tolerance response (Huang et al., 2016b; Leverrier, Vissers, Rouault, Boyaval, & Jan, 2004). Using sweet whey (50% w/w) as the drying medium, two *Propionibacteria acidipropionici* strains were spray dried with a pilot spray dryer under around 140 °C inlet temperature and 60 °C outlet temperature. A high degree of viability following spray-drying was obtained, with around 100% survival and 10^{10} CFU g^{-1} cell counts in the powder (Schuck, Dolivet, Méjean, Hervé, & Jeantet, 2013). In our recent work, *Propionibacteria freudenreichii* ITG P20 was found to survive better than *Lactobacillus casei* BL23 (70% versus 40%), even under harsher drying conditions (180 °C T_{inlet}, 73 °C T_{outlet} versus 140 °C T_{inlet}, 63 °C T_{outlet}) (Huang et al., 2016a). However, compared to *Lactobacillus* (*Lb.*) and *Bifidobacteria*, studies involving the drying of *Propionibacteria* (*P.*) are still rare.

Streptococcus (*S.*) is usually more resistant than *Lactobacillus* to spray-drying; for instance, *S. thermophilus* was shown to survive better than *Lb. delbrueckii* ssp. *bulgaricus* in spray-dried yoghurt (Bielecka & Majkowska, 2000; Kumar & Mishra, 2004), and *S. thermophilus* CCRC14085 survived better than *Lb. acidophilus* CCRC 14079 in spray-dried fermented soymilk (Wang, Yu, & Chou, 2004). The threshold temperature at which damage is caused to microbial cells is usually within the range of the upper limit of growth temperature of the microbial species (Foerst & Kulozik, 2011). Thus the spray-drying resistance of *S. thermophilus* is probably linked to its greater thermotolerance. In another observation, *Lb. paracasei* NFBC 338 was however found to survive as successfully as *S. thermophilus* (Kearney et al., 2009). This finding indicates that certain strains within a usually fragile specie may be as resistant as bacteria from a generally robust specie.

When compared within the *Lactobacillus* genus, *Lb. plantarum* is a specie with relatively robust stress tolerance (Ferrando, Quiberoni, Reinhemer, & Suárez, 2015). Mille, Beney, and Gervais (2005) showed that the osmotic tolerance of *Lb. plantarum* was