Chapter

Wettability of Probiotic Powders: Fundamentals, Methodologies, and Applications

Mohamed A. Ali, Joël De Coninck and Hary L. Razafindralambo

Abstract

Wettability is a macroscopic consequence of microscopic phenomena occurring at the fluid-solid interfaces. This functional property is crucial for the formulation of wettable powders in food and non-food sectors. Basically, powder wettability is mostly assessed through the contact angle measurements of solid particles reacting with dispersing media, by either the sessile drop method or the capillary rise technique. Among the most popular bioactive agents nowadays are probiotics and their metabolites, which are receiving a growing interest for their beneficial effects on our ecosystem health. As live functional ingredients, probiotics are mainly available in a powder form that is sensitive to the environmental stress factors during processing and storage steps. It is therefore crucial to understand and control their wettability, regarding their performance, dispersibility, and stability when probiotic particles come into contact with dispersing media and body fluids. The proposal chapter aims to review: (1) the theoretical aspects of powder wettability by considering compact and porous materials; (2) the analytical tools and methodologies of measurement, including sessile drop and capillary rise methods using models Lucas-Washburn equation and Darcy's law; and (3) the applications to probiotic powders as functional ingredients in food and agricultural sectors.

Keywords: wettability, probiotic powders, contact angle measurement, capillary rise method, porosity, cell surface hydrophobicity, cell viability

1. Introduction

Wettability is a functional property that represents the wetting degree of a solid. Among the macroscopic consequences of nano- and microscopic phenomena occurring at fluid-solid interfaces, it is governed by the balance between adhesive and cohesive forces, representing the assembly strength of different and identical surfaces, respectively [1]. Such phenomena are naturally encountered in our daily life, or technologically shaped for our necessities [2]. The common examples of solid wettability are observed with drops of water standing out on lotus leaves or repelling on waterproof materials, as well as with agrochemical dispersion preparations spreading

on plant surfaces [3–7]. Adhesives, anti-icing, bio-mimicking, boiling, coatings, fibers, freeze-casting, inks, micro/nanoelectromechanical systems, paper, and petrochemicals also take part of a non-exhaustive list of applications involving wettability [8–15].

When an amount of liquid (e.g. drop of water) comes into contact with a porous or nonporous solid surface (e.g. flat or granular solid), its displacement until an equilibrium position depends on the force resulting from the interfacial tensions at the contact line of three immiscible phases (solid/liquid/gas) (**Figure 1**). The changes in the resulting interfacial tension or free energy define the contact angle (CA), which expresses the wetting degree of the solid surface by the liquid phase [16]. When the CA is lower than an arbitrary value (e.g. $\theta < 90°C$), the surface is qualified as hydrophilic whereas it is known as hydrophobic for high CA (e.g. $\theta > 90°C$). A value superior to 150°C is a characteristic of a superhydrophobic surface [17].

For powder materials, the wettability is often quantified by the contact angle (θ) of compressed disc- or packed bed-prepared particles, which depends on the surface and bulk properties, composition of particles, wetting liquid characteristics, and physicochemical conditions such as the temperature, pH, ionic strength, and so on [18]. The powder wettability plays a crucial role in coating, dispersion as a precursor step to dissolution, and powder processing such as granulation and other practical usages. Several techniques are available for powder wettability determination through the contact angle measurement of solid particles reacting with dispersing media by the static and dynamic sessile drop method or by the capillary rise technique [19].

Most food and non-food (e.g. pharmaceuticals, detergents, minerals) ingredients and products are in powder form, which is constituted by numerous particles and granules, in pure or mixture form of multiple components [20, 21].

There are many powder wettability case studies of either organic or inorganic-based compounds reported in the scientific literature over the last five years (**Table 1**). However, less investigations have been conducted on powders that contain microorganisms such as probiotics and derivative products.

Probiotics are live microorganisms, when administered in adequate doses and under appropriate conditions, and can be benefits for the host through different action mechanisms [33]. In fact, they can act as (1) competitors for nutrients and adhesion sites with intestinal or plant pathogens; (2) metabolite producers, including bacteriocins, organic acids, antioxidants, enzymes, and biosurfactants; and (3) immunomodulators [34]. Often used as functional ingredients, probiotics find their potential applications in foods, feeds, cosmetics, pharmaceutics, and agriculture sectors [35–39]. Belonging mainly to lactic acid bacteria (LAB) such as Lactobacilli and

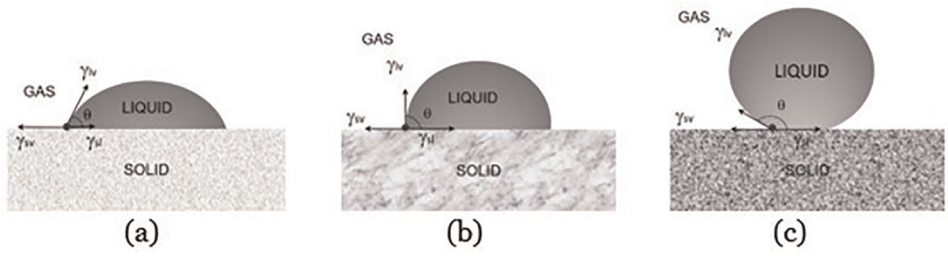


Figure 1.
Illustration of liquid drop formed between three immiscible phases with different contact angles θ: (a) hydrophilic θ <90°C, (b) hydrophobic θ = 90°C, and (c) superhydrophobic surfaces.

Materials	References
Coffee powder	[22]
Wheat/cereal flours	[23]
Detergent granules	[24]
Pectin agglomerates	[25]
Cocoa beverage powder	[26]
Milk powder	[27]
Excipients	[28]
Drugs	[29]
Silica particles	[30]
Limestone	[31]
Talc	[32]

Table 1.
Examples of wettability studies on various organic and inorganic powders.

Bifidobacteria, or yeasts, probiotics are among the most investigated research topics today, owing to their beneficial effects on our overall ecosystem, involving activities and interactions among human, animal, and plant species, soils and the environment [40].

Their external surfaces are surrounded of components with different molecular classes (e.g. proteins, polysaccharides, peptidoglycans, etc.) and specific structures (e.g. pili), which are responsible for their most surface properties and functionalities such as hydrophobicity, adhesion, and aggregation capacities. Microbial cell surfaces are vital to their survival for interacting with the environment. It is assumed that microbial cells adhere to surfaces through the interactions between extracellular compounds biosynthesized by cells or from external (e.g. coatings) and surfaces [41]. It is generally recognized that there exists a correlation between cell adhesion capacity and surface hydrophobicity, which can be indirectly measured by the water contact angle [42]. Microorganisms are considered hydrophilic for values less than 20° and hydrophobic for values superior to 50° [43, 44].

Moreover, probiotic-based products are industrially manufactured and commercially available in powder particles, in most cases under various solid states rather than dispersed in liquid forms, by successive fermentation, liquid–solid phase separation, and drying processes [45]. It is therefore important to focus scientifically and technologically on the probiotic powder wettability, which is a performance indicator, directly or indirectly in terms of (1) cell capacity in adhering to surfaces; (2) product dispersibility in a fluid for some preparations before use in formulations or uptake as diet supplementation; (3) cell viability and product stability for limiting the contact with humidity and air through the powder porosity or permeability; and (4) coating material compatibility and processing efficiency for cell protection.

The current chapter deals successively with (1) the theoretical aspects of powder wettability; (2) the practical methods and techniques of wettability determination; and (3) the applications to probiotic powder wettability for food and agricultural products.

2. Theoretical aspects on powder wettability

2.1 Basics on contact angle

When a water drop enters in contact with a surface, or a liquid comes in contact with a vertical and infinitely wide plate or porous solid and powders, and rises by capillary effect, the contact angle gives an insight of these wetting phenomena. With a macroscopic view, the contact angle represents the angle formed at the intersection of the interfaces liquid-solid and liquid-vapor by applying a tangent line at a point from the so-called "three-phase contact line", where the solid, liquid, and vapor phases co-exist (see **Figure 1a**). Contact angles are not only limited to the liquid-vapor interface on a solid but also applicable to the liquid-liquid interface on a solid. Depending on the media (surface or porous structure), the contact angle measurement and the tool to be used are different.

2.2 Flat surface (Young's equation)

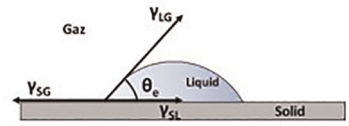
On an ideal flat surface (partial wetting), Young's equation allows the determination of the liquid contact angle in equilibrium θ_e. It represents the static contact angle value based on the interfacial energy balance between the solid, liquid, and gas surrounding the liquid at the triple line contact (**Figure 2**). Young described first the entire phenomenon in 1805, which was mathematically formalized by Dupré while also discovered elsewhere by Laplace. Thus, this Young-Dupré law is commonly called "Young-Laplace equation" [46–49].

2.3 Rough surfaces (Wenzel model & Cassie-Baxter model)

In the case of non-ideal flat surfaces (roughness added), two contact angle measurements are involved. On the one hand, the Wenzel model adds roughness to

$$\cos\theta_e = \frac{\gamma_{SG}-\gamma_{SL}}{\gamma_{LG}} \quad \text{(Eq.1)}$$

(a)

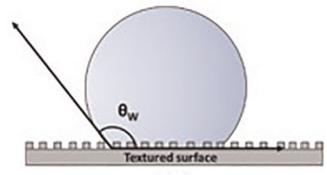


(b)

Figure 2.
Flat solid surface cases: (a) Young's equation; (b) liquid drop with an equilibrium contact angle (θ_e).

$$\cos\theta_W = R_W \cos\theta_e \qquad R_W = \frac{Real\ surface\ area}{Projected\ area}$$

(a)



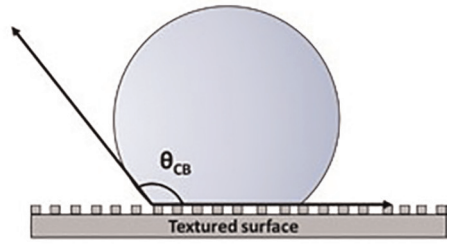
(b)

Figure 3.
Rough surfaces described by the Wenzel model: (a) apparent contact angle θ_w determination, θ_e being the equilibrium value used in Eq. (1), and $R_W \geq 1$ represents the ratio between the real surface area over the projected area; (b) drop in Wenzel state.

$$\cos\theta_{CB} = f_A \cos\theta_A + f_B \cos\theta_B \quad \text{(Eq.2)}$$

$$f_A + f_B = 1$$

$$\cos\theta_{CB} = f_A (1 + \cos\theta_A) - 1$$



(a) (b)

Figure 4.
Rough surfaces described by the Cassie-Baxter model: (a) Cassie-Baxter contact angle θ_{CB} determination, f_A and f_B being the fractions of surfaces A and B; (b) drop in Cassie-Baxter state.

complete Young equation (Eq. (1)), and on the other hand, the Cassie-Baxter model depicts surfaces with chemical heterogeneities.

2.3.1 Wenzel model

The Wenzel model illustrates how the drop is in contact through the roughness of surfaces that Young's equation does not take into account. Thus, the drop is pinned on the surface, forming an apparent value of contact angle, which is different to the equilibrium one (**Figure 3**). This angle is modified by a factor called the Wenzel roughness R_w [50–54].

Such phenomenon appears when the solid surface is completely in contact with liquid under the droplet. However, air can be trapped below the drop that tends to lower its energy (e.g. fakir and nails board). In this situation, the drop contact angle is described by the Cassie-Baxter model.

2.3.2 Cassie-Baxter model

The Cassie-Baxter model describes the rough surface as a succession of two different surfaces SA and SB with a resulting wettability that depends on two contact angles θ_A and θ_B [53, 55, 56]. In this case, the contact angle θ_{CB} is a function of the fractions of surfaces A, a first-level roughness feature with solid width and air spacing structure, and surfaces B, a second level roughness at the base of a second-level capillary bridge (**Figure 4**), as defined in Eq. (2).

Theoretical studies show the importance of roughness and its impact on the Wenzel to Cassie-Baxter transition. In fact, the double scale roughness is not always the key parameter to enhance the transition. This also depends on R_W factor and the decrease of f_A [57–59].

2.4 Capillary rise phenomenon (Washburn & Darcy models)

Trees, oil extracting, ink absorption, liquids and sponge, sugar and coffee are among common applications where one can witness a capillary rise phenomenon. It has been described many years, even centuries, ago. When a both-side opened tube is approached to a liquid reservoir surface, the liquid tends to fill the tube. The thinner the tube, the higher the liquid rises inside. The height or height square (or the

equivalent mass) versus time is always monitored. This curve has two parts, a dynamic component (rising) and a steady state component. At certain time, the liquid reaches a limit height (h) represented by Jurin's law (Steady state) represented by Eq. (3) [48, 60].

$$h = \frac{2\gamma cos\theta_e}{\rho g R} \tag{1}$$

where θ_e is the contact angle, R the radius of the tube, ρ the density of the liquid, γ the surface tension, and g the gravity.

2.4.1 Lucas-Washburn model

The dynamic part of the capillary rise is driven by the Lucas-Washburn equation (LWE). As it is a time-dependent phenomenon [5, 48, 61–66], the equation analytical expression including the gravity and inertia parts is:

$$\frac{2}{R}\gamma.cos\left(\theta_e\right) = \rho g h + \frac{8}{R^2}\eta h.\frac{dh}{dt} + \rho.\left(h\frac{d^2h}{dt^2} + \left(\frac{dh}{dt}\right)^2\right) \tag{2}$$

where R represents the radius of the tube, ρ the density of the liquid, γ the surface tension, g the gravity, and η: viscosity.

By neglecting the gravity and inertia and assuming h to 0 when time equals 0, and using the Taylor's expansion [67], the LWE is obtained from the above equation:

$$h = \sqrt{\frac{2t}{b}} \tag{3}$$

where

$$b = (8/R2)/_L Rcos(e)$$

By replacing the height h with the mass m of the liquid through the relation $m = \rho.\pi R^2$h [68, 69], the following equation can be obtained:

$$m(t)2 = \frac{\rho 2\pi 2R^5\gamma cos\theta}{2\eta} \bullet t \tag{4}$$

This Lucas-Washburn's equation possesses limitation because the inertial forces are neglected.

2.4.2 Darcy model

The capillary rise previously presented does not take into account the permeability, even though there is a capillary constant in the LWE (geometry of the porous material). However, the approximation done with the critical radius is not enough to determine the permeability of materials (porosity). Darcy's law describes thus the wicking in porous media.

Darcy's discovery in 1856 was based on the study of the Dijon fountains, the ground water, and permeability by defining through theoretical and experimental works a universal formula related to the flux of water in sand [48, 70–72]. By changing the pressure (height of the reservoir), a linear relation between the flux and the pressure was observed, which was at the origin of Darcy's law, as follows:

$$h(t).\frac{dh(t)}{dt} = \frac{k}{\eta}.\frac{\gamma}{R} \tag{5}$$

where k being the porous material permeability (can be related to viscosity), R: radius of the section, η: viscosity, and γ: surface tension.

By integrating the Darcy equation, it is easy by using the previous arguments to write

$$h = \sqrt{\frac{2.t}{b_{eff}}} \tag{6}$$

where

$$b_{eff} = \frac{\eta R}{k.\gamma} = \frac{\frac{8}{R^2}\eta}{\frac{2}{R}\gamma.cos\,(\theta_e)} = \frac{4\eta}{\gamma.R.cos\,(\theta_e)} \tag{7}$$

From Eqs. (8) and (9), we can deduce

$$h = \sqrt{\frac{2.k.\gamma.t}{.R_{eff}}} \tag{8}$$

This equation indicates that the permeability k is proportional to h^2 and R_{eff} represents the effective radius. From the kinematics of the imbibition in a porous media, the effective radius can thus be extracted, characterizing its permeability or equivalently its porosity.

3. Practical methods for powder wettability determination

The wettability of powders can be determined by various techniques described in detail by Alghunaim et al. [19]. These include the sessile drop, Wilhelmy plate, and liquid penetration methods. In this section, only two practical methods of contact angle measurements based on the sessile drop and capillary rise are briefly described for their possible application to probiotic powders (Section 4).

3.1 Sessile drop method

The sessile drop method can be applied to solid surface prepared after compacting powder in a disc or pellet under well-defined conditions of high pressure (70–700 MPa). It is the most common technique for determining the wettability of powders. The static contact angle measurement is performed by depositing a small amount of liquid drop on the disc or pellet while recording its spreading. A software is always

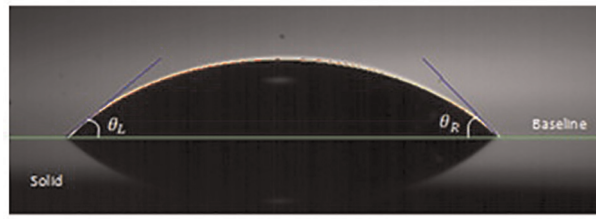


Figure 5.
Drop of water fitted by a software.

used for analyzing the contact angles (edge detection) with the programmed functions (i.e. straight line, circle or Laplace fitting). In this way the contact angle is extracted by fitting the baseline between the drop/the substrate (interface liquid/solid) and the shape of the drop as represented in **Figure 5**. The method provides the right and left contact angles θ_R and θ_L.

For hydrophobic and superhydrophobic surfaces, other methods like Johnson and Dettre [73] and the sliding method can be used, respectively [74–78]. A hysteresis representing the difference between the advancing and the receding contact angle can be deduced in dynamic measurements [79].

3.2 Capillary rise method

Powder samples are introduced into a glass tube for preparing a packed-bed column with support at the bottom (e.g. filter paper). The tube is then put in contact to a liquid surface, and the liquid penetration front is monitored as a function of time. The change in mass of the sample attached to a microbalance is recorded and plotted against time to obtain the contact angle information. In practice, the packed-bed column is first tested with a completely wettable solvent ($\cos\theta = 1$) for determining the capillary constant R_C from the equation in Section 2.4.1. Once R_C is known, the desired liquid can be used to evaluate the contact angle θ. This method has a limitation because one assumes that the porous material is comparable to a succession of fine tube each one having a critical radius R_C (**Figure 6**). Assuming this fact is not representative for all porous materials [80–84]. Indeed, powder and fiber bundles are more complicated because the pores are not always vertical. The porous material possesses

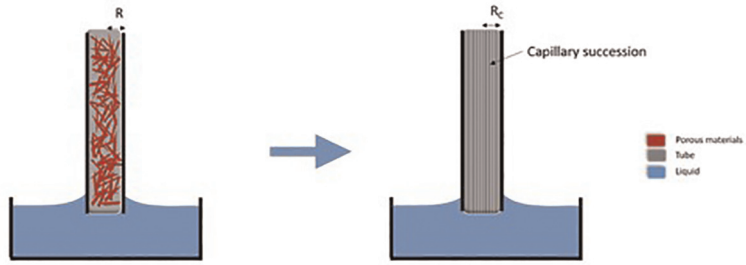


Figure 6.
Analogy between real porous material and capillary succession approximation.

its own distribution inside the tube. Therefore, the way how the powder and the fibers are compact plays a key role in the robustness and the repeatability of the results.

4. Applications to probiotic powders

The wettability of probiotic powders is first a good indicator of surface cell hydrophobicity, and therefore the cell adhesion capacity through liquid contact angle measurements. Such a functional property is also important for powder product dispersibility and compatibility with coating materials.

Probiotic powders are heterogeneous and complex solid materials that generate high variability data of water contact angle measurements. Therefore, the determination of their wettability is a difficult task and needs a judicious choice of available techniques and methods. In this section, we first describe and discuss the different methodologies used for probiotic powders before illustrating their practical importance in food and agricultural areas.

4.1 Surface wettability

A first approach is to prepare a compact surface by compressing the probiotic powder sample under high pressure conditions for making pellets, and then measuring the liquid contact angle by the sessile drop method. This method has been used for the first time for determining the water angle contact of the cell surface of the probiotic multistrain sample [85]. Neither visible cracks nor chemical alteration has been observed before and during the measurement of the static contact angle. This method has provided similar results compared to the static advancing water contact angle technique used for the same sample [45]. The combination of the sessile drop method with the compressed disc preparation under well-defined press conditions provides reproducible data and appears as a very practical methodology for determining the probiotic surface contact angles.

A second approach is to prepare a multilayer or lawn of probiotics by passing through an appropriate filter a liquid dispersion of powder particles under vacuum. The filter on which the probiotic lawn adheres is then treated by a first step of moisture equilibration time for several minutes, followed by a second one of air drying. This is the most commonly used method for determining the liquid contact angle, and distinguishing hydrophobic microorganisms to hydrophilic ones [43]. It has some advantages in preparing smooth and homogenous microorganism layers, and is more convenient for fragile cells [86]. Such a procedure has been optimized to lower the variability in the results of contact angles by searching the best moisture equilibrium time and moisturizing medium [43]. Through this method, it has, for instance, recently been shown the contribution of two main probiotic components (*L. bulgaricus* and *S. thermophilus*) of a multistrain sample (vivomixx) for their respective surface hydrophilicity [45]. Some water contact angle data measured by this technique are available in the literature for some bacterial probiotics such as *L. acidophilus* (66–80°), *L. rhamnosus* (33–86°), *L. plantarum* (25–79°), and *S. thermophilus* (23°).

4.2 Bulk wettability

A third approach to assess the wettability of probiotic powder is the use of the capillary rise technique measuring the amount of liquid penetrating a bed column of

sample over time, and applying a mathematical model that fits the penetrating rate profile of a liquid up a tube packed. Even though the capillary rise technique is by far the popular method for determining contact angles of powders or porous materials [69], it has rarely been applied to probiotic powders. Such a method has, for instance, been used for characterizing the wettability of a multistrain powder sample of probiotics, showing two regimes of the liquid penetrating rate profile [85]. The first one is a power law regime for the first few moments while the second one can be described using Darcy's law. The use of this modeling approach has led to the possibility of assessing the particle-packed bed permeability and porosity through an effective radius determined by the semi-empirical Kozeny-Carman approach [85]. These physical properties are interesting for predicting some performance of probiotic strain such as product stability and cell viability during the powder storage. In fact, high powder porosity or permeability promotes the presence of air (oxygen) and/or moisture in inter- and intra-particle pores, accelerates the oxidative process of cell membranes, and reduces rapidly the cell viability rate.

4.3 Practical use in food and agricultural areas

Most ingredients used in product formulations are available in a powder form, owing to many practical advantages in transportation, handling, processing, formulation, packaging, and stability [20].

The wettability of powders plays important roles in product preparation, engineering, stability, and performance, since it is the first step of powder dispersion that is of crucial importance for the process of making a dispersion [87].

4.3.1 Food applications

For probiotic-based food products and ingredients used in the preparation of fermented foods and diet supplements, the degree of wetting needs to be at the right value for ensuring both good preparation during the hydration and high stability during the storage. Some examples of commercialized products are listed in **Table 2**. Probiotic powders are currently formulated with a mixture of components, including mono- or multistrain microorganisms and other active and functional ingredients and excipients (e.g. prebiotics, antioxidants, cryoprotectors, anti-agglomerates, diluents, lubricant, colorant, binder, coating agent, sweetening agent, anti-caking agent, binders, etc.) (**Table 3**). Binders are, for instance, adhesives that provide the cohesiveness essential for the bonding of solid particles during the process of agglomeration [88]. Consequently, their wettability is an important criterion for the powder dispersibility when rehydrate or reconstituted, and powder stability related to porosity during the storage. This also impacts the viability of probiotic strains, which are sensitive to the environmental conditions such as humidity and temperature.

The wettability of probiotic powders may vary as a function of other components within their formulations. When the latter contain prebiotics, mainly carbohydrate-based compounds, the products are called synbiotics. It has been demonstrated that prebiotics can change the probiotic surface properties, and therefore would impact the wettability of whole products [89]. It is also well known that free fats in the surface reduce wettability whereas some surface-active agents, especially those exhibiting dispersing capacity commonly improve wettability in dried containing fat products [88].

Products	Microbial probiotics
Infant milk formulation	*Lactobacillus rhamnosus Bifidobacterium longum*
Oat and rice powder	*Bifidus* BL
Baking mix	*Bacillus coagulans*
Passion fruit juice powder	*Lactobacillus plantarum* S20
Synbiotic goji berry powder	*Bifidobacterium animalis* subsp. *lactis* (Bb12), *B. longum* (Bb46), and *Lactobacillus casei*
Spray-dried raisin powder	*B. coagulans*
Almond milk powder	*L. plantarum* ATCC 8014
Tubers-Cassava	*Saccharomyces cerevisiae*, *L. bulgaricus*
VSL#3	*Lactobacillus acidophilus*, *L. plantarum*, *L. casei*, *Lactobacillus delbrueckii* subsp. *bulgaricus*, *B. breve*, *B. longum*, and *B. infantis*, *Streptococcus salivarius* subsp. *Thermophilus*

Table 2.
Some examples of commercialized products of probiotic powders.

Excipients in probiotic powders	Functions
Microcrystalline cellulose	Binder/diluent
Rice maltodextrin	Binder/diluent
Silicon dioxide	Gliding/anti-caking agent
Magnesium stearate	Lubricant
Hydroxy propyl methyl cellulose	Suspending/viscosity agent

Table 3.
Some excipients in probiotic powder formulations.

4.3.2 Agricultural applications

Agricultural applications of probiotic powders include animal and plant health and growth, as illustrated with some examples in **Table 4**. Probiotics have been recognized to be benefits to the host animal as feed supplements and animal products (e.g. poultry, ruminant, pig, and aquaculture) in improving food safety. Their use aims at reducing, even substituting antibiotics to control pathogens in poultry production [90].

For probiotic-based agriproducts such as microbial feed supplements, pesticides, and anti-weeds, an optimum powder wettability is required for ensuring high dispersibility in the liquid media preparation, but also for maximizing the spreading and penetrating properties with regards to the target materials (e.g. plant leaves).

In aquaculture, probiotic activities mainly result from the production of antimicrobial metabolites and the attachment or adhesion to intestinal mucus for competing with pathogens.

Microorganism	Name of product	Plant pathogens/photosystem
Ampelomyces quisqualis M-10	AQ10 Biofungicide	Powdery mildew on fruits
Azospirillum spp.	Biopromoter	Paddy, millets, oilseeds, fruits, vegetables
Bacillus subtilis GB03	Kodiak	Growth promotion; Rhizoctonia
Bacillus pumilus	YiedShield	Soil-born fungal pathogens
Delftia acidovorans	Bioboost	Canola
Pseudomonas chlororaphis	Cedomon	Leaf strip, net blotch
Streptomyces griseoviridis K61	Mycostop	*Phomopsis* spp., *Botrytis* spp.
Trichoderma harzianum T22	RootShield	*Pythium* spp., *Rhizoctonia solani*
Pseudomonas spp.	Proradix	*Rhizoctonia solani*

Table 4.
Applications of probiotic powders in agriculture (adapted from [39]).

Plant health benefits and growths in using probiotics involve direct mechanisms through beneficial microbes-host plant interactions, including adherence and colonization steps, or indirect ones due to the antagonistic activity against plant pathogens. Probiotic plant antagonism includes inhibition, competition for nutrients, and degradation of pathogenicity factors [91].

4.3.3 Probiotic viability and survival applications

Probiotics can provide health benefits when they reach the targets with a high number of viable cells. In fact, many microbial probiotic strains are sensitive to external environmental conditions such as high acidity, moisture, temperature, and oxygen level. Two main strategies can be employed in maintaining the viability, or reducing the mortality of probiotic strains: (1) using additional ingredients such as prebiotics in a synbiotic formulation for supporting cell viability throughout processing, storage, distribution, gastrointestinal, and environmental stress conditions; (2) protecting cells by using encapsulation technology or coating processes.

4.3.3.1 Synbiotic formulations

It is recognized that combining prebiotics and probiotics together in synbiotic powder formulations may boost the viability of probiotic strains [89]. Prebiotics are substrates that serve as probiotic nutrients, and mainly consist of carbohydrate compounds such as inulin, oligosaccharides (e.g. GOS, XOS), and fructooligosaccharides [92]. Thus, the wettability of their mixture is an important indicator for ensuring the synbiotic performance, either in synergism or in complementary [93], dispersibility in a fluid, and stability during storage.

4.3.3.2 Encapsulation and coating processes

Encapsulation and coating processes are often used for protecting the probiotics and synbiotics against environmental stress conditions in order to maintain a high level of viability, stability, and performance [94]. It uses various food-grade

biopolymers, mostly derived from polysaccharides (e.g. gum Arabic, alginate, chitosan, resistant starch, etc.) and proteins (e.g. milk and soy proteins), and different technologies, including the bulk or microscale matrix encapsulation systems and the individual cell encapsulation via nanocoatings [95]. The first method is based on the immobilization of probiotics into a gel matrix (e.g. hydrogel systems) whereas the second one is based on the formation of nanofilms around individual probiotic cells (e.g. cytoprotective approaches based on silica, graphene, metal-polyphenol nanoshells, etc.).

In both cases, the wettability of probiotic powders before and after encapsulation or coating processes appears important for operating convenient choices of coating agents and processes but also for the final product performance. In fact, the microbial probiotic surface properties such as hydrophobicity and polarity as well as the permeability/porosity of the powder have an impact on the compatibility and interactions with the coating or encapsulation materials for ensuring an appropriate stability and permeability of the formulated products. Based on several investigations, the survival rate of probiotic strains may vary between 68 and 94% during the storage and digestion, depending on the coating or encapsulating materials and methodologies used [94]. Nevertheless, such protective processes are not necessary for the spore-forming bacteria such as *Bacillus* strains which convert from vegetative into resistant spore forms by naturally producing a protective shell under harsh conditions, including high temperature, pressure, and acidity, as well as heat, desiccation, radiation, and oxidation conditions [95]. It might also be the case of Lactobacillus strains through self-encapsulation mechanisms by producing a thicker layer of EPS, when the environmental factors and stress conditions of fermentation are modified [96].

5. Conclusion

The wettability of probiotic powders deserves a great scientific and technological attention, as for other food and non-food ingredients and products in various sectors. Beyond its evident importance in the dispersibility and stability of the powder containing live microorganisms and other components in contact with fluids, it is a crucial indicator of the cell adhesion capacity and cell viability improvement through encapsulation and coating processes. Its accurate determination with the appropriate techniques and data processing models is the key to progress in getting insight into the probiotic action mechanisms, and in improving the probiotic containing product qualities and performance. However, there are only a few available scientific data from probiotic powder wettability studies in the literature compared to contact angle measurements with various techniques. Three sample preparation and measurement techniques such as powder compact discs and microbial lawns by sessile drop, and a packed-bed column using rise capillary, can be distinguished. Subsequently, two fitting models based on Washburn equation and Darcy's law may be used based on the experimental recorded data. In particular, Darcy's law combined with the semi-empirical Kozeny-Carman approach provides a potential prediction of powder porosity or permeability. This methodology will open a new research route on the impact of the microbial powder particle size, shape, aggregation, adhesion, biofilm formation on the formulation performance and product stability, as well as on the cell viability and activities for human, animal, plant, and environment, in short, on our ecosystem health.

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Author details

Mohamed A. Ali[1], Joël De Coninck[1] and Hary L. Razafindralambo[2,3]*

1 Physics of Surfaces and Interfaces Laboratory, UMons, Belgium

2 ProBioLab, Campus Universitaire de la Faculté de Gembloux Agro-Bio Tech/ Université de Liège, Gembloux, Belgium

3 BioEcoAgro Joint Research Unit, TERRA Teaching and Research Centre, Microbial Processes and Interactions, Gembloux Agro-Bio Tech/Université de Liège, Gembloux, Belgium

*Address all correspondence to: h.razafindralambo@uliege.be

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