Ionic Diffusion in Spherified Calcium Alginate Gels: A Laboratory Experiment

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Introduction
Dilute water solutions of sodium alginate are used in molecular cooking and the dairy industry as thickening and gelling agents (Barham et al., 2010) and also as edible films. Typically, they are obtained from brown algae or seaweeds and form stable gels in the presence of calcium ions.

Calcium alginate gels can be easily prepared in the form of small solid spheres by dropping, with a syringe or a pipette, the sodium alginate solution into a water bath of calcium ions (“direct method”). After rinsing the calcium alginate spheres, fully or just partially jellified, their external pH can be easily regulated using ordinary acid and/or basic solutions. The difference of the pH value between the inside and the outside of the spheres drives the diffusion of H$_3$O$^+$ ions from the solution to the liquid phase, which is trapped in the porous, sponge-like, calcium alginate gel. If a suitable pH indicator is added to the initial sodium alginate solution, the time-dependent pH variation inside the sphere can be easily detected as a gradual change in its colour, and also by an evolving colour gradient. This colour change is observed moving from the surface towards the centre of the solid sphere. As one would expect for a solid, no change of shape and/or size of the sphere occurs, whereas the fast and complete diffusion from the outside to the core of the sphere represents the typical behaviour of liquid systems. This experiment clearly shows how calcium alginate gels surprisingly share some physical properties of both states of matter.

The dual solid/liquid nature of calcium alginate gels, strikingly highlighted by the preceding example, has been extensively used over many decades in several fields, from dentistry to the food and dairy industry, molecular gastronomy and, more recently, regenerative medicine, lithium-ion batteries, self-healing materials, and biodegradable disposable water pouches. Further details and references are reported in the section “Uses of Sodium Alginate”.

Sources and Chemistry of Alginic Acid and Sodium Alginate
Plant (eukaryotic) cells are characterized by a semi-rigid cell wall enveloping the phospholipidic membrane. Brown algae cell walls are composed of three polymers: cellulose (long and stiff fibres, giving mechanical endurance), hemicellulose (a branched sugar-based polymer) and alginic acid (Cosgrove, 2005). These last two materials act as a “glue”, giving flexibility to the stiff cellulose fibre matrix. Alginic acid is typically present as sodium, calcium or magnesium alginate. Terrestrial plants, and in particular their fruits, contain large amounts of pectin instead of alginic acid as a second cellulose glue: this material can be used as a gelling agent in the preparation of fruit preserves, conferring on them their jelly-like consistency, aspect, and mechanical and textural properties, as well as increasing their resistance to bacterial biodegradation.

The major industrial source of alginic acid is cultivated marine brown weeds of the *Laminaria* family. The process of sodium alginate production is schematically shown in Figure 105.1 (McHugh, 1987). It shows how pH, as well as Na$^+$ and Ca$^{2+}$ concentrations, can be used to separate and purify water-soluble sodium alginate from chopped seaweeds following two different pathways.

From the chemical point of view (Figure 105.2), alginic acid and its salts are copolymers made of random blocks of β-D-mannuronate (M) and α-L-guluronate (G) monomers (Draget et al., 2005).

As shown in Figure 105.3a, the glucosidic bond between two neighbouring G units leads to the formation of a cavity, which can be filled by positive ions, e.g., Ca$^{2+}$, attracted by the negative charges of the hydroxyl and carboxyl groups of α-L-guluronate. Alginic acid at basic pH and its sodium salts are soluble in water thanks to the great number of strong hydrogen bonds that can be formed with the solvent and to the electrostatic repulsion between negatively charged carboxylate groups, which does not favour the aggregation of polymer chains. Conversely, at low pH, alginic acid is protonated and as such, not soluble in water (Draget et al., 2005).

If calcium ions are present in a sodium alginate solution, they fill the available cavities formed by the GG pairs and bind strongly to them (Figure 105.3a). At the same time, calcium ions are large enough to protrude from each cavity and coordinate a still free GG pair cavity in a different position or belonging to...
another nearby polymer chain. These opposite pairs of GG cavities filled by the same calcium ion are the elementary units of the so-called “egg box model” (Figure 105.3b) (Grant et al., 1973; Li et al., 2007).

The appearance of these casual 3D junctions and linkages is responsible for the insolubility of calcium alginate, since they readily transform the sodium alginate liquid solution into a sponge-like gel (Figure 105.4).

The formation of a calcium alginate gel is not thermoreversible: when heated, water is permanently lost and spheres become dry. Nonetheless, a calcium alginate gel can still be restored to its constituents through approaches aimed at weakening and eventually destroying the gel structure by reducing either the number of calcium ions or the number of GG cavities available to form the basic egg box structures. Three approaches are easy to perform with students in a laboratory experiment on a water solution containing alginate spheres: (1) to lower the solution pH below the pKₐ of alginic acid in water, so that the polymeric chains become insoluble; (2) to increase the pH and use ethylenediaminetetraacetic acid (EDTA), which strongly binds calcium ions and subtracts them from the egg box formation equilibrium; (3) to increase the pH and use an excess of Na₂CO₃, which acts as a source of Na⁺ ions and removes Ca²⁺ by forming solid insoluble CaCO₃. The third is the most common industrial process used to prepare the sodium alginate salt (Figure 105.1).

**Uses of Sodium Alginate**

**Medicine and Dentistry**

Stiff and strong calcium alginate gels have been used for a long time to prepare dental casts, and more recently, other innovative applications have been reported. For instance, reconstruction of damaged cardiac tissues after a stroke can be helped using a 3D matrix gel with trapped gold nanofilaments (Dvir, 2011).

Moreover, calcium alginate spheres can be used as vehicles for drug delivery. Alginate capsules are used to cover healthy cells that can be grafted into patients to repair damaged tissues and/or to produce active ingredients without causing adverse reactions to the immune system (Dettmar et al., 2011; Lee and Mooney, 2012). For instance, drugs, like insulin, can be provided to a patient by inserting a healthy cell that produces insulin in an alginate capsule. Insulin diffuses through the wall of the capsule into the patient’s bloodstream, while patient antibodies are...
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unable to reach the host cell inside the capsule because their size is larger than the calcium alginate porosity (Tan and Takeuchi, 2007; Martinez et al., 2012; Tahtat et al., 2013).

In a similar way, alginate salts can be used for cartilage and bone tissue engineering (Liu et al., 2017).

Innovative Materials

Algicnic acid and its derivatives have been used as components of highly stretchable and tough hydrogels, as reported by Niekraszewicz and Niekraszewicz (2009) and Sun et al. (2012). High-capacity Li-ion batteries can be produced with Si-nanoparticles embedded in alginate gels (Kovalenko et al., 2011; Gu et al., 2014; Yoon et al., 2014).

Alginate gels are employed also as biodegradable blob-like water containers called “Ooho”, produced by the Skipping Rocks Lab. The “Ooho” spheres are made by dropping ice into solutions of calcium salt and sodium alginate, leading to small water volumes enclosed in membranes. Besides degrading in four to six weeks, the capsules are edible, since they are made of 100% brown algae. The manufacturing process is easy and cheap,
cocktails and salads to create small caviar-like spheres, which release a flavour burst in the mouth when they are crushed by the teeth. Sodium alginate is first mixed with the tasty/flavoured liquid to be spherified. This liquid is then dropped into a solution with calcium chloride (CaCl₂), calcium lactate or calcium lactate gluconate, generating a sealing membrane, which forms the spheres. After this treatment, the spheres can be removed and rinsed in distilled water, ready to be served in cocktails.

Alginate gels are also used for low-cost production of lactose-free milk by room temperature enzymatic degradation with lactase. The lactase enzyme is first immobilized inside the calcium alginate spheres during the spherification. These spheres are then employed as a solid-state catalyst in a continuous flow reactor, and the raw milk is percolated through them, thus allowing the disaccharide lactose molecules diffusing inside the spheres to be split into their glucose and galactose monomeric units, which then do not cause allergic reactions in humans (Woodward, 1985).

**Physical Properties of Calcium Alginate**

In the direct method, the thickness of the external skin of calcium alginate spheres can be optimized by choosing the time they remain in the calcium bath: shorter times lead to a thin skin, longer ones to a thicker one and eventually to a completely jellified sphere.

In addition, the liquid nature of the gel can be probed by modifying external conditions and observing how they influence the inner part of the sphere and its shape (Chuang et al., 2017). Alginate gels resemble wet sponges: they are characterized by liquid-filled nano or micro canals and cavities, able to let small molecules flow through them (Shapiro and Cohen, 1997; Boontheekul et al., 2005). Therefore, by modifying the pH value of the medium outside and using a pH indicator, one can verify that the pH of the inner part of the sphere changes. The colour change does not occur instantaneously, just as when a tea bag slowly modifies the colour of warm water during the infusion period of tea, even though, for the jellified spheres, the indicator starts changing from the outside and slowly reaches the inside.

The underlying physical process is diffusion, an entropy-driven net mass movement of a chemical species from a region of higher concentration to a region of lower concentration, which in a liquid is assisted by thermal random motion of solute and solvent particles. Diffusion takes place also in the absence of concentration gradients, and in this case, the disordered motion produced by random collisions is termed Brownian or random-walk. In both cases, the distance travelled by a given particle, or by the concentration front, is proportional to the square root of the elapsed time.

**Experimental Protocol**

In this section, we describe in detail the various steps of the procedure adopted for the preparation of calcium alginate spheres and for detecting the diffusion of protonated water inside them by observing the colour change of a suitable pH indicator contained in the spheres, as schematically depicted in Figure 105.5.
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Preparation of Sodium Alginate Solution

The first step consisted in preparing a sodium alginate solution at an adequate concentration.

In general, the smaller the sodium alginate concentration, the higher the gel porosity and the faster the diffusion process. After testing several concentration values, we decided to use a solution at 1% w/w, even though this is still fairly concentrated with respect to culinary concentrations (~0.5% w/w): this is a good compromise between mechanical resistance of the spheres and diffusion time of H$_3$O$^+$ ions inside them.

The pH of this sodium alginate solution was measured with a universal indicator as almost neutral (Figure 105.6).

Sodium alginate is characterized by slow solubilization kinetics and presents technical drawbacks. In order to obtain a uniform solution, clots should be broken, first with a mortar and then with an ultrasonic bath. In molecular cooking, this is not a viable option for chefs, so alginate is usually prepared 24 h before usage by mixing water – possibly salty – and sodium alginate with a blender. The solution we obtained in this way, which incorporated air bubbles, was put overnight in a fridge: even though the low temperature increases the solution viscosity, it also reduces gas solubility and allows air bubbles to escape the mixture, yielding a clear and transparent liquid. Some chefs also use vacuum packaging machines, when available, to help to remove the air bubbles.

Once we obtained a homogeneous solution, we divided it into two batches and added, as pH indicators, phenolphthalein (P) in the first one and bromothymol blue (B) in the second batch (Figure 105.7). The indicator amount was one drop for each gram of alginate solution. During this step, it is important to take care to mix slowly: this avoids incorporating air bubbles again into the alginate. Note that phenolphthalein in these amounts is not completely soluble in alginate solution and partially precipitates, making the solution slightly opaque.

Jellification and Conservation Bath

In order to obtain a more uniform jellification, the Ca$^{2+}$ ions should be introduced into sodium alginate solution through a fine powder of CaCO$_3$, so that the dispersion is homogeneous. When the sodium alginate solution is dropped with calcium carbonate into an acidic solution, the H$_3$O$^+$ ions diffuse into the sphere and induce CaCO$_3$ solubilization, generating Ca$^{2+}$ ions in situ. Since

![Flowchart for calcium alginate droplets’ preparation and diffusion experiment.](image)
for the scope of this work this would have been an unnecessary expedient, we decided to use a CaCl$_2$ solution as a source of Ca$^{2+}$ ions.

We prepared a solution of CaCl$_2$ at 2% w/w. As before, we divided it into two batches and added, as pH indicators, P to the first batch and B to the second, in order to have the same indicator concentration as in the alginate solution (one drop of indicator for each gram of CaCl$_2$ solution). We then brought the pH value to 10.0–10.5 by adding NaOH. The pH was measured with an Amel 338 pH meter.

Note that the indicator was added both to the CaCl$_2$ and to the sodium alginate solution before dropping the latter into the former, in order to avoid a net flow of the colourant from the CaCl$_2$ solution to the inside of the droplet and vice versa: in this way, we do not have to take care of pH indicator diffusion, which could be slower compared with that of H$_3$O$^+$ and Ca$^{2+}$.

The use of a pH indicator should allow a clear distinction between the basic and acidic colours. For this reason, we chose to analyse both phenolphthalein and bromothymol blue. The first indicator is magenta in basic solution and colourless at acid pH, while the second one turns from blue to yellow for the same pH variation.

Once the jellification bath was prepared, we dropped sodium alginate 1% w/w solution into it with a plastic pipette from a suitable and constant height (~5 cm from the surface of the jellification bath) in order to obtain spherical droplets of uniform dimensions (Figure 105.8, where we used a solution without pH indicator just to make the droplets more visible). Indeed, the impact with the liquid from an excessive height would deform the droplet, while dropping from an insufficient distance from the solution surface would produce droplets with a “tail”. Other possible deformation effects are shown in Figure 105.9.

We let the drops rest inside the solution for 20–30 min to allow the diffusion and jellification processes to conclude. After this period, one can reasonably assume that ions (H$_3$O$^+$ and Ca$^{2+}$) and indicator are uniformly distributed inside the spheres.

We then transferred the droplets into a second conservation bath (Figure 105.10), with the same composition as the first one, since the pH and the Ca$^{2+}$ concentration of the original bath were slightly decreased after the diffusion inside the droplets. This transfer procedure must be repeated until the pH of the bath stays constant: we observed that one additional step is typically sufficient. We suggest letting the droplets rest in the last bath for at least 15 min.

Two consecutive pH measurements, one performed at the end of this procedure and the other one on the following day, gave nearly identical results (pH ≈ 10.5).

**Preparation of Acidic CaCl$_2$ Solutions and Measurements of Turning Times and Diameter of Spheres**

After the spherification was complete and the system had reached equilibrium in the original bath conditions, we took some spheres of similar size from the solution and placed them into three
different 2% w/w CaCl₂ solutions (the same as used for the jellification process) at pH values of 2.0, 3.0 and 3.5, respectively. The higher H₃O⁺ concentration pushes ions to diffuse from the bulk of the solution into the droplet core: this provokes a gradual variation of pH inside the spheres, detected thanks to a change in the indicator colour, starting from the external skin and moving towards the centre. In Figure 105.11 we show some photos of two calcium alginate droplets containing the pH indicators P and B, respectively, which change their colour as a consequence of the H₃O⁺ diffusion: in (a) phenolphthalein turns from magenta to colourless, and in (b) bromothymol blue turns from blue to yellow.

We measured the turning time (τ, i.e., the time required by the pH indicator inside a droplet to completely change its colour due to pH variation) for a total of five droplets for each value of pH. Timings were recorded with a stopwatch, and at the end of the diffusion process, we measured the diameter of the spheres with a calliper (Figure 105.12). We also took time-lapse videos of the turnings to analyse them with a "simulated" digitalized spectrophotometric procedure, as explained in the next section.

As a summary of the experimental protocol, there follow step-by-step instructions, also illustrated in Figure 105.13.

1. Preparation of 500 g of 1% w/w sodium alginate solution. (We suggest the preparation of at least 250 g of sodium alginate solution, since it must be blended with a mixer, which is difficult with small volumes of mixture.)
1.1. Weigh 5 g of sodium alginate and add this to 495 g of distilled water.
1.2. Blend with a mixer and let it de-gas overnight in a fridge (this can take some hours).
1.3. Put 10 g of sodium alginate solution into a vessel, add 10 drops of 1% w/w phenolphthalein (P) (1:1

**FIGURE 105.10** Conservation bath with P indicator.
(Photo by Studio Fotografico Marco Fortini, Bologna, Italy)

**FIGURE 105.11** Effect of H₃O⁺ diffusion inside two calcium alginate spheres as a function of time. (a) Phenolphthalein changing from magenta to colourless and (b) bromothymol blue changing from blue to yellow.
(Photo by Studio Fotografico Marco Fortini, Bologna, Italy)

**FIGURE 105.12** Measurement of sphere diameter with a calliper.
water-ethanol solution) and mix carefully, avoiding air incorporation.

1.4. Put 10 g of sodium alginate solution into another vessel, add 10 drops of 0.04% w/w bromothymol blue (B) (water solution) and mix carefully, avoiding air incorporation.

1.5. Measure the solution pH with a universal indicator and take note of the value.

2. Preparation of 2% w/w CaCl$_2$ solution.

2.1. Weigh 21 g of CaCl$_2$ and dissolve in 1030 g of distilled water.

3. Jellification and conservation bath.

3.1. Calibrate the pH meter for basic pH measurements.

3.2. Put 550 mL of CaCl$_2$ solution prepared as in point 2.1 into a beaker with a magnetic stirring bar, place it on a magnetic stirrer and switch it on.

3.3. Using the pH meter, bring the pH value to 10.0–10.5 by adding 0.5 M NaOH solution (take note of the final value).

3.4. Transfer 200 mL of CaCl$_2$ solution into another beaker and add 20 drops of P indicator (this will be the jellification bath).

3.5. Transfer 30 mL of CaCl$_2$ solution into another beaker and add 30 drops of P indicator (this will be the conservation bath).

3.6. Check the pH value of the conservation bath (point 3.5) and, if necessary, adjust it to the value measured at point 3.3.

3.7. By means of a plastic pipette cut at a suitable internal diameter (2–4 mm), drop the sodium alginate solution with P indicator (point 1.3) into the jellification bath (point 3.4) so as to obtain about 20 droplets with a good spherical shape (as described in section “Jellification and conservation bath”; to obtain droplets with a good spherical shape, the sodium alginate solution should be dropped at a distance of about 5 cm from the CaCl$_2$ solution).

Let them rest inside the jellification bath for 20–30 min.

FIGURE 105.13 Graphic illustration of the experimental procedure.
3.8. Transfer the droplets with a good spherical shape into the conservation bath (point 3.5) and let them rest there for at least 15 min.

3.9. Check the pH value of the conservation bath (point 3.5) and, if necessary, adjust it to the value measured at point 3.3. If the pH differs more than 0.5 pH units from that value, we suggest preparing another conservation bath, transferring the droplets into it and letting them rest there for another 15 min.

3.10. Repeat the procedure from point 3.4 to 3.9 with the B indicator.

4. Preparation of acidic CaCl₂ solutions and measurements of turning times and sphere diameter.

4.1. Calibrate the pH meter for acidic pH measurements.

4.2. Put 150 mL of the CaCl₂ solution prepared at point 2.1 in a beaker with a magnetic stirring bar, place it on a magnetic stirrer and switch it on.

4.3. Using the pH meter, bring the pH value to 3.5 by adding 0.5 M HCl solution (take note of the final value).

4.4. Put 25 mL of the solution obtained at point 4.3 in a beaker, put a sphere with P indicator into the solution and measure the time it takes to completely change its colour.

4.5. Repeat the procedure of point 4.4 so as to have at least three measurements.

4.6. At the end of the diffusion process, measure the diameter of each droplet with a calliper.

4.7. Following the procedure from point 4.2 to 4.6, prepare 150 mL of pH 3 and 150 mL of pH 2 CaCl₂ solutions and measure the turning times at these pH values and the droplet diameters.

4.8. Repeat the same measurements for droplets with B indicator.

In Figure 105.14, we show a schematic representation of the diffusive processes taking place into the droplets in the various phases of the experiment.

Results

We collect here the observations obtained for five drops of alginate with phenolphthalein and five with bromothymol blue.

The data reported in Figures 105.15 and 105.16 show turning times \( \tau \) relative to the droplets with P indicator and to those with B indicator. We observed that \( \tau \) slightly changes depending on the nature of the indicator. Indeed, the two indicators possess a different turning pH range: 8.0–10.0 for P and 6.0–7.6 for B, resulting in faster turning of phenolphthalein compared with bromothymol blue.

Figure 105.15 shows \( \tau \) as a function of the droplet diameter. Note that, on average, increasing the size of the spheres will increase as well the time required for the pH inside the droplets to change, in principle with a quadratic dependence on the radius.

In Figure 105.16 we show the turning time averaged over droplet diameter (\( \langle \tau \rangle \)) versus CaCl₂ solution pH. Note that \( \langle \tau \rangle \) increases with CaCl₂ solution pH. This is due to the fact that the pH difference between the droplets and the solution (\( \Delta \text{pH} \)), which is the diffusion driving force, decreases. Indeed, inside the gel porosity, we can reasonably assume that there is molecular diffusion, described by the second Fick’s law: this states that the diffusion rate is proportional to the Laplacian of the concentration, which is linked to the difference of H₃O⁺ concentration between the droplet core and the solution bulk. As expected, the

![FIGURE 105.14 Schematic representation of the diffusive processes taking place into the droplets in the various phases of the experiment: initial neutral sodium alginate drop, jellification process after the dropping in a basic CaCl₂ solution (pH = 10.5), basic jellified droplet at pH ≈ 10.5, diffusion of H₃O⁺ ions after the immersion of the droplet in an acidic CaCl₂ solution (pH < 3.5), acidic jellified droplet at pH < 3.5.](image-url)
two curves have similar trends, and the one relative to B indicator lies above that relative to P indicator.

Digital Spectrophotometric Analysis

Lastly, we simulated a digitalized spectrophotometric analysis performed, during the diffusion process, on a sphere with P indicator and on another one with B indicator. This analysis allows us to count as a function of time, for each frame, the number of coloured pixels, which is linked to the absorbance signal of a real spectrophotometric measure. This signal is connected to the number of pH indicator molecules that have still not turned, \( N(t) \), and hence, to the diffusion progress. However, we have to take into account that we analyse circular 2D frames, while a hypothetical absorbance signal is associated with a sample volume. To tackle this problem, we start defining the fraction \( x(t) \) as the ratio between the number of magenta (for P indicator) or bluish (for B indicator) pixels, \( N_p(t) \), and the total number of pixels in the cropped frame, \( N_{tot} \):

\[
x_p(t) = \frac{N_p(t)}{N_{tot}}.\]

As we explained earlier, \( N_p(t) \) is proportional to the area of a circle \( C \) (Figure 105.17), which is the 2D projection of the sphere \( S \) containing the fraction of pH indicator that has not turned yet.
C and S having the same radius, \( r_S(t) \), we obtain

\[ x_p(t) \approx N_p(t) \approx r_S^2(t), \]

and, considering that the volume of S, \( V_S(t) \), is proportional to \( r_S^3(t) \), we finally get

\[ V_S(t) \approx r_S^3(t) \approx x_p^{3/2}(t). \]

The volume \( V_S(t) \) is also proportional to \( N_I(t) \), since

\[ N_I(t) = V_S(t)C_I, \]

where \( C_I \) is the pH indicator concentration inside the droplet. Therefore, \( x_p^{3/2}(t) \) can be assumed to be proportional to \( N_I(t) \), and then to the absorbance signal.

In Figure 105.18, we show the fraction of magenta pixels \( (x_p) \) raised to 3/2 versus time obtained from a time-lapse video of a droplet with P indicator immersed into a pH 2.0 solution of CaCl\(_2\). Similarly, in Figure 105.19, we report the fractions of bluish and yellowish pixels \( (x_p) \) raised to 3/2 versus time for a droplet with B indicator put into the same CaCl\(_2\) solution.

The frames of the videos have been cropped around the sphere itself, and the RGB values for each pixel have been collected. These three colour values have been converted into luminance, saturation and hue values (www.niwa.nu/2013/05/math-behind-colorspace-conversions-rbg-hsl/). All pixels without grey hue values have been converted into colours using a “Hue Range Map” (www.workwithcolor.com/color-names-01.htm). In the case of P indicator, we calculated the fraction of pixels containing orange and brown, red or magenta, and for B indicator, those containing cyan, green or blue (for the bluish) and yellow or orange and brown (for the yellowish).

For both droplets, the turning times obtained by image processing (Figures 105.18 and 105.19) are in good agreement with those obtained previously (~6 min for P droplet, ~10 min for B droplet; see Figure 105.16 at pH = 2.0).

The image analysis is superior to the visual one, since it is quantitative, providing the time evolution of the number of pixels for different colours, which in principle could be used for testing kinetic models of the diffusion process inside the sphere.

The trends in the fraction of magenta and bluish pixels, correlated with the average H\(_3\)O\(^+\) concentration inside the droplet, reflect those predicted by Fick’s law; indeed, the diffusion rate (i.e., the curve slope) decreases with time, resulting in an exponential-like decay.

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**FIGURE 105.17** Representation of the circle C, 2D projection of the sphere S, which contains the molecules of pH indicator not yet turned, and its radius \( r_S \).

**FIGURE 105.18** Simulated digitalized spectrophotometric analysis performed on a time-lapse video of a calcium alginate sphere with P indicator immersed into a pH 2.0 solution of CaCl\(_2\). The graph shows the fraction of magenta pixels \( (x_p) \) raised to 3/2 versus time.
Conclusions

We described a simple experiment that allows us to verify that the hydrogel nature of calcium alginate confers physical properties that one normally associates either with a solid (well-defined shape) or with a liquid (fast diffusion of solvated ions). Moreover, we provided a detailed procedure that can be followed to organize an easy and inexpensive laboratory experience that, even if shown to high school students, can be adjusted, with proper modifications, also for other educational levels. Indeed, alginate spheres can represent a useful tool to show how diffusive processes occur into a gel: the $\text{H}_3\text{O}^+$ ion diffusion can be qualitatively followed by eye, or quantitatively through image processing, thanks to the presence of a pH indicator inside the sphere.

Since the diffusion coefficient is about ten times greater for $\text{H}_3\text{O}^+$ than for $\text{Ca}^{2+}$, and the diffusion time is inversely proportional to the diffusion coefficient, our results for $\text{H}_3\text{O}^+$ can be used also to estimate the jellification time for sodium alginate solutions, which is directly linked to the diffusion time of $\text{Ca}^{2+}$ ions. This knowledge can be useful for performing partial jellification – a typical practice in the field of molecular cooking – where the aim is to obtain a jellified external “skin” and a liquid core, so that the flavour contained inside the sphere spreads once it is bitten.

And finally … a bit of Molecular Gastronomy art!

Supplementary Material

Additional images, videos and information about our group are available on the website https://spheresmoleculargastronomy.netsons.org/.

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Dedication

We dedicate this chapter to the memory of our beloved friend and gifted scientist Roberto a.k.a. “Bebo” Berardi, who most sadly left us in January 2020.
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