Supplemental Materials for Biodegradable Tracer Particles for Underwater Particle Image Velocimetry

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I. ALL BIODEGRADABLE PARTICLES TESTED

This study evaluated a range of biodegradable particles for use in flow visualization experiments, including cosmetic-grade and food-grade particles. These particles were chosen for their availability, environmental safety, and potential to serve as substitutes for commercial tracer particles. Table I provides a detailed summary of the properties of each particle type, including size, density, optical characteristics, and solubility.

Table II lists commercially available tracer particles with sizes comparable to those used in PIV experiments in water, supplied by vendors such as Dantec Technologies, LaVision, and Potters Industries. The materials used for these tracers include borosilicate glass, polyamide, and ceramics, which are non-biodegradable and cannot be digested by aquatic organisms, posing potential environmental and ecological concerns.

II. STARCH PARTICLES VARIABILITY

Figure 1 presents microscope images of selected biodegradable starch particles (potato, corn, and arrowroot starch) to illustrate particle size and morphology across different sources and manufacturers. The images demonstrate that, within the same type of starch, particle size and morphology remained relatively consistent despite originating from various brands.

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	Biodegradable particles	Density compared to DI water	Diameter	Color	Laser scattering	Water solubility
1	Jojoba beads	$<< 1.0$ g cm^{-3}	mm scale	None	Yes	No
2	Walnut shell powder	> 1.0 g cm^{-3}	mm scale	Brown	Yes	No
3	Lemon peel granules	> 1.0 g cm^{-3}	mm scale	None	Yes	No
4	Pumice powder	> 1.0 g cm^{-3}	sub-mm scale	None	Yes	No
5	Baking powder	~ 1.0 g cm^{-3}	um scale	None	Yes	No
6	Baking soda	Not applicable	um scale	None	No	Yes
7	Bee pollen	~ 1.0 g cm^{-3}	um scale	Orange	Yes	No
8	White Sonora wheat flour	~ 1.0 g cm^{-3}	um scale	None	Yes	No
9	Ceylon cinnamon	~ 1.0 g cm^{-3}	um scale	Brown	Yes	No
10	Colloidal oatmeal	~ 1.0 g cm^{-3}	um scale	None	Yes	No
11	Chaga mushroom powder	~ 1.0 g cm^{-3}	um scale	Brown	Yes	No
12	Corn starch	~ 1.0 g cm^{-3}	um scale	None	Yes	No
13	Potato starch	~ 1.0 g cm^{-3}	um scale	None	Yes	No
14	Arrowroot starch	~ 1.0 g cm^{-3}	um scale	None	Yes	No
15	Black sea salt	> 1.0 g cm^{-3}	mm scale	Black	No	Yes
16	Kelp granules	> 1.0 g cm^{-3}	mm scale	Green	Yes	No
17	Soy scrub	> 1.0 g cm^{-3}	mm scale	Light brown	Yes	No
18	Apricot seed powder	> 1.0 g cm^{-3}	mm scale	Brown	Yes	No
19	Cacao powder	~ 1.0 g cm^{-3}	um scale	Brown	Yes	No
20	Stearic acid particles	< 1.0 g cm^{-3}	mm scale	None	Yes	No

TABLE I. Overview of the cosmetics-grade and food-grade particles tested. Cosmetic particles (Jojoba beads, Walnut shell powder, Lemon peel granules, Pumice powder, Colloidal oatmeal, Black sea salt, Kelp granules, Soy scrub, and Apricot seed powder, Stearic acid) were sourced from Wholesale Supplies Plus, Inc. Food-grade particles included Baking powder, Baking soda, Potato starch, Arrowroot starch, and Cacao powder (Thrive Market); Corn starch (Ach Food Companies); Bee pollen (Sunfood Superfoods); Chaga mushroom powder (Om Mushroom Superfoods); Ceylon cinnamon (Simply Organic); and White Sonora wheat flour (Dry Storage). Among those particles, baking soda and black sea salt are soluble in water.

For instance, potato starch particles tend to be larger and predominantly elliptical in shape. Corn starch particles, in contrast, were noticeably smaller, with a rougher surface texture. Arrowroot starch particles were the smallest among the three types and exhibited smoother surfaces compared to corn starch.

The consistency in size and morphology within each starch type suggests that biodegrad-

	Commercial particles	Diameter (μm)	Shape	Materials	Manufacturer
1	Hollow glass sphere (HGS)	10	spherical	borosilicate glass	Dantec Technologies
2	Silver-coated hollow glass spheres (S-HGS)	10	spherical	borosilicate glass	Dantec Technologies
3	Polyamid seeding particles (PSP)	20	round but not exactly spherical	polymerisation processes	Dantec Technologies
4	Polyamide particles HQ	20	spherical	polyamide	LaVision
5	Silver-coated hollow ceramic spheres	55	spherical	ceramics	Potters Industries

TABLE II. Commercially available particles for PIV experiments in water. Notes: In row 2, Dantec Technologies offers silver-coated hollow glass spheres in other particle sizes, including 5 μm and 50 μm. In row 4, LaVision also offer other particles sizes, including 60 μm.

able starch particles are reliable and reproducible alternatives to commercial tracer particles. Their widespread availability and predictable characteristics make them particularly promising for use in underwater flow visualization experiments. Additionally, the ability to select starch types based on particle size and texture offers flexibility in experimental design, ensuring optimal particle behavior for specific flow conditions or imaging requirements.

III. VISCOSITY MEASUREMENTS OF STARCH AND WATER MIXTURE

To evaluate the impact of biodegradable starch particles on fluid viscosity, viscosity measurements were conducted using mixtures of starch particles and deionized (DI) water, with commercial tracer particles and pure DI water serving as reference cases.

For each measurement, 0.05 g of particles (either starch-based or commercial) were thoroughly mixed into 50 mL of DI water. This mixture resulted in a highly concentrated suspension of tracer particles, exhibiting significant opacity, far exceeding the typical particle seeding concentration used in PIV experiments. The kinematic viscosity of each mixture was measured using a viscometer (Ubbelohde semi-micro viscometer, size 75, Cannon Instrument Company), and the process was repeated three times to ensure consistency and reliability of the results.

The one-way ANOVA analysis was conducted to evaluate whether there were significant differences in viscosity across different groups of experiments. The results showed an F-statistic of 1.998 and a corresponding p-value of 0.171. Because the p-value is greater than the commonly used significance threshold of 0.05, we fail to reject the null hypothesis (i.e., no true difference between groups). This indicates that any observed variations in viscosity

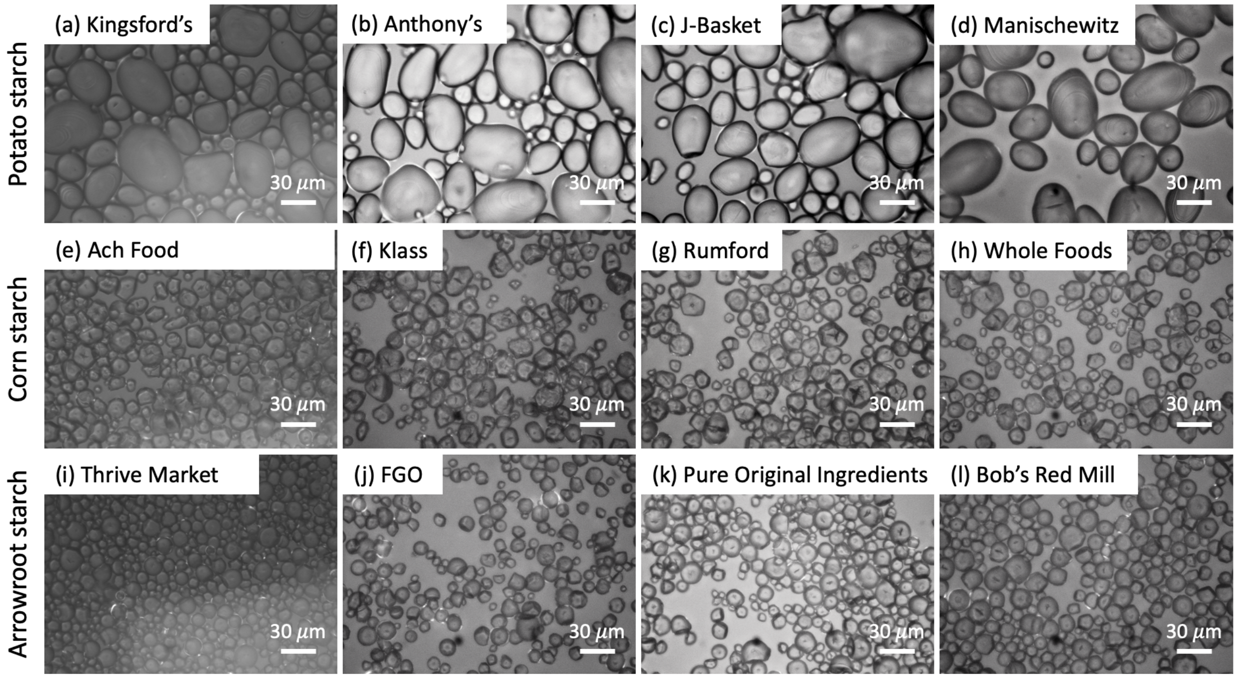

FIG. 1. Biodegradable particles manufactured by different companies under the microscope. The first row shows different potato starch particles: (a) Anthony's organic potato starch, (b) J-BASKET Katakuriko potato starch, and (c) Manischewitz pure potato starch. The second row shows different corn starch particles: (e) organic corn starch from Ach Food Companies, (f) Klass corn starch, (g) Rumford Non-Gmo corn starch, and (h) corn starch from Whole Foods Market. The third row shows different arrowroot starch particles: (i) arrowroot powder from Thrive Market, (j) FGO organic arrowroot powder, (k) Pure Original Ingredients arrowroot powder, (l) Bob's Red Mill arrowroot flour.

among the groups are likely due to random chance rather than a systematic difference. Therefore, we conclude that there is no statistically significant difference in viscosity between the groups in the data.

The results indicate that the viscosity difference between DI water and the starch particle mixtures is small and negligible, demonstrating that the addition of biodegradable starch particles does not significantly alter the fluid viscosity. Furthermore, the viscosity of the starch particle mixtures closely matches that of the commercial particle mixtures. This consistency highlights the suitability of biodegradable starch particles as substitutes for commercial tracers in flow visualization experiments, as they exhibit comparable behavior without introducing unwanted viscosity changes.

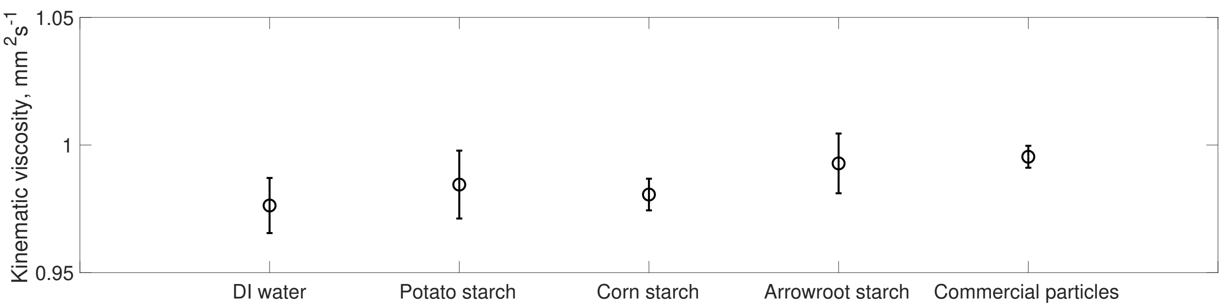

FIG. 2. Viscosity measurements of starch particles and water mixture, with DI water and commercial particles and water as reference. In all the measurements with particles, 0.05 g particles were mixed in 50 mL DI water. For each case, viscosity measurements were repeated three times. The viscosity difference between DI water and starch particles + water mixture is small and negligible, and the viscosity of starch particles + water mixture is similar to that of commercial particles + water mixture.

Overall, these findings confirm that biodegradable starch particles can be used in PIV experiments without compromising fluid properties, further supporting their viability as an environmentally friendly alternative to conventional tracer particles.

IV. PH TEST OF PARTICLE-WATER MIXTURE

pH tests were conducted for all particle-water mixtures listed in Table I to evaluate their effect on water acidity or alkalinity. pH strips (API Aquarium Test Strips) were used for these measurements. To use the strips, each strip was dipped into the particle-water mixture for a few seconds then removed. After allowing about 30 seconds for the color to stabilize, it was compared to the pH chart to determine the corresponding value. For efficiency, the particles were first tested in groups to identify any pH changes. If a change was detected, the group was further divided to pinpoint the specific particles responsible for the change.

The results indicated that most biodegradable particles had minimal impact on the water's pH, maintaining it close to neutral. However, baking powder and baking soda exhibited a noticeable effect on pH levels, with baking soda, in particular, causing a substantial increase in alkalinity. These findings highlight the importance of considering particle composition when using them in pH-sensitive experiments or applications.

V. EXPERIMENTAL SETUP FIGURE

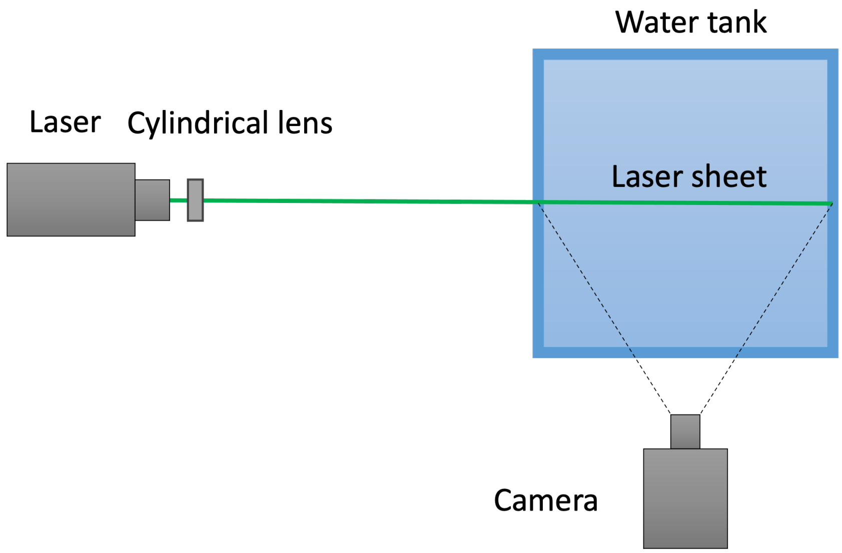

FIG. 3. PIV system setup (top view), including a green laser sheet generated using a laser head and a cylindrical lens, illuminating the tracer particles in the water tank; camera to record the motion of the particles; and tank for underwater experiments. The tank used for the brine shrimp experiment measures 5 cm $\times$ 5 cm $\times$ 5 cm, while the tank for the translating foil and jellyfish experiments measures 31.75 cm x 16.51 cm x 20.95 cm.