

Folic Acid-Based Coacervate Leading to a Double-Sided Tape for Adhesion of Diverse Wet and Dry Substrates

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ABSTRACT: Adhesives are crucial both in nature and in diversified artificial fields, and developing environment-friendly adhesives with economic procedures remains a great challenge. We report that folic acid-based coacervates can be a new category of excellent adhesives for all kinds of surfaces with long-lasting adhesiveness. Aided by the electrostatic interaction between the π - π stacked folic acid quartets and polycations, the resultant coacervates are able to interact with diversified substrates via a polyvalent hydrogen bond, coordination, and electrostatic interactions. The adhesivity to wood is superior to the strong commercial glues, but without releasing any toxic components. Upon evaporating water, the coacervate can be casted into a non-adhesive flexible self-supporting film, which restores the adhesive coacervate immediately on contacting water with original adhesive ability. In this way, the coacervate can be facily tailored into a double-sided tape (DST), which is convenient for storage and application under ambient conditions. Given its excellent adhesive performance, release of nontoxic gases, and convenience in storage and application, the folic acid-based DST is very promising as a new adhesive material.

KEYWORDS: folic acid, polycation, adhesive, coacervate, double-sided tape



INTRODUCTION

Adhesives play vital roles in a vast number of industries, as well as in medical treatments and everyday life.^{1–5} Adhesive glues displaying good flow ability are of particular interest since they are able to form a homogeneous adhesive layer between irregular surfaces, thus providing reliable adhesion. The most commonly used adhesive in various circumstances is cyanoacrylate. When applied at the interface between two tissues, cyanoacrylate instantly polymerizes into a glassy polymer and bonds strongly with the substrates via covalent interactions. However, cyanoacrylate has many associated problems: (1) it works poorly in the presence of moisture or on wet surfaces as it is quickly cured by water before adhering to the substrates; (2) the adhesive layer is stiff and constrains the movements of the soft tissues; and (3) the cyanoacrylate releases cytotoxic compounds during service; and (4) the low storage temperature of 2–8 °C limits its shelf life.⁶

To tackle these problems, green adhesives inspired by natural mussel adhesive proteins have recently been developed.^{7,8} Different from cyanoacetate that loses its adhesive ability on wet surfaces, adhesive proteins display excellent adhesive ability toward any surface and can even perform underwater adhesion.^{9–11} It has been unraveled that the adhesive proteins usually self-assemble into cross-linked three-dimensional (3D) networks to strengthen the mechanical strength, whereas the highly concentrated polar or charged

groups on the side chains function as the super polyvalent bonds to fix them on the surface.^{12,13} Since the side chains of adhesive proteins are rich in catechol (dopamine) and various amino acids, chemists have synthesized various adhesives by covalent tethering of catechol or amino acid side chains to polymer backbones.^{10,14,15}

Albeit the exciting success, the preparation of those materials usually involves multistep procedures, time-consuming processes, harsh conditions, and toxic reagents.^{2,16,17} These challenges and environmental concerns prompted scientists to seek supramolecular adhesives that are capable of facile preparation in all-aqueous media. Recently, Lee and co-workers have reported a simple strategy to produce a wet adhesive via co-assembly of tannic acid and poly(ethylene glycol) in water, where the tannic acid shows structural similarity to adhesive proteins that have abundant catechol groups.¹⁸ Based on these unique structural features, other outstanding tannic acid-based complex adhesives were also developed.^{2,5,16} On the other hand, considering that adhesive

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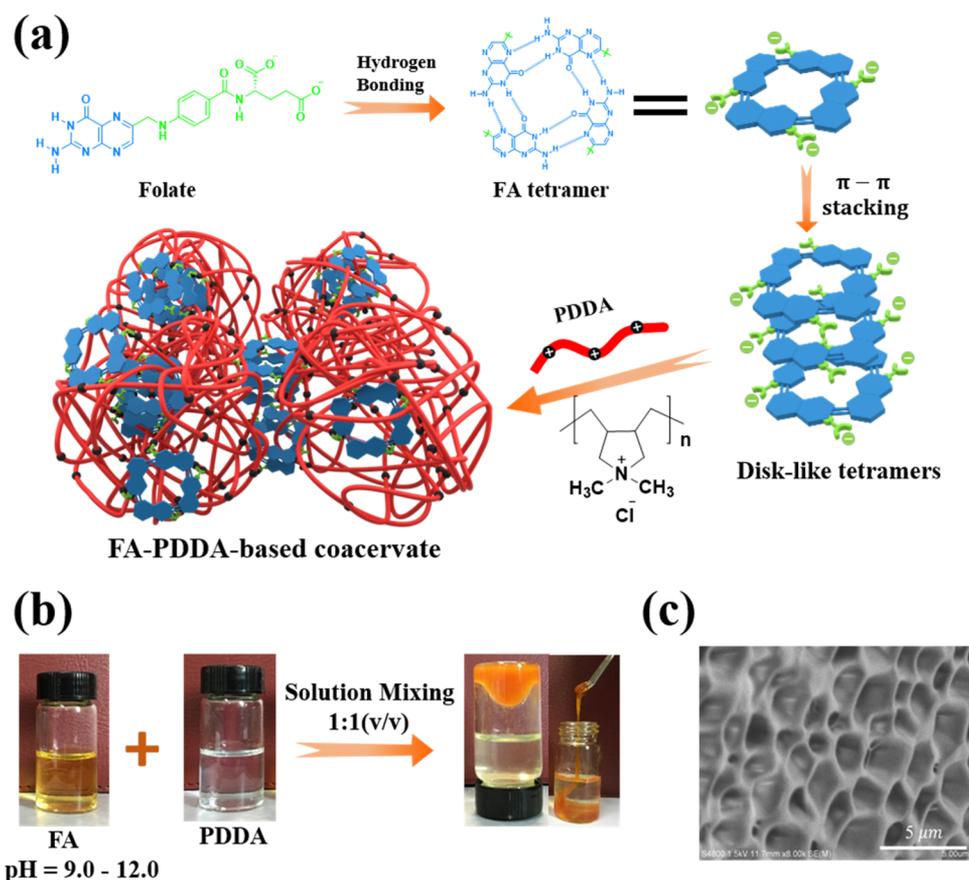


Figure 1. (a) Formation mechanism of the PF-C-X coacervate-based adhesives. (b) Photos of mixing the aqueous solution of FA and PDDA to prepare the coacervate adhesive. (c) SEM image for the lyophilized coacervate.

proteins are composed of a large number of amino acids, Li and co-workers took a further step of using the natural and renewable amino acid monomers in combination with polyoxometalates (POMs) to form wet adhesives.¹⁹ These noncovalent cross-linking strategies open up a wide variety of possibilities for using noncovalent interactions to construct effective adhesives.

Folic acid (also known as pteroyl-L-glutamic acid) is a naturally abundant B vitamin that can be extracted from various natural supplies, such as green leafy vegetables, legumes, and fruits.²⁰ In industry, folic acid can be chemically synthesized at a large scale and low cost via a simple one-step chemical reaction.²¹ Folic acid is essential to the human body, because it is necessary for the production and maintenance of new cells. This is especially important during the periods of rapid cell division and growth such as pregnancy and infancy when it is necessary to take specific dosages of folic acid on a daily basis.²² Till now, folic acid has been extensively studied due to its antitumor effect.^{23,24} However, so far, it has never been considered in the field of adhesion. Folic acid carries carboxyl, carbonyl, and amidogen groups, which can provide hydrogen bonding, metal complexation, and electrostatic interaction with other components, enabling effective interaction with various surfaces. This bonding ability resembles the catechol moieties, the main component consisting of the mussel adhesive proteins,^{9,25} suggesting that composite materials based on folic acid are probably a new category of excellent adhesives.

For that to occur, the folic acid molecules have to form soft materials with robust bulk mechanical strength. It is well known that folic acid is able to form a quartet in water that further undergoes $\pi-\pi$ stacking.²⁶⁻²⁸ This led us to hypothesize that the folic acid quartets may facilitate the formation of soft matter, which provides polyvalent interactions like natural adhesive proteins. Water-soluble cationic polyelectrolytes with quaternary ammonium salt structure, such as poly(diallyl dimethylammonium) chloride (PDDA), exhibit cohesive adsorption and antibacterial properties and have been employed in various biological and medical applications.^{29,30} Herein, we demonstrate how the use of PDDA to drive the one-step noncovalent cross-linking of folic acid quartets in aqueous media results in the formation of adhesive coacervates with long-lasting adhesiveness. Strikingly, owing to its excellent flowing ability, the coacervate can be further cast into non-adhesive flexible freestanding films upon evaporation of water, which may immediately transform into a viscous adhesive coacervate under water spray. In this way, we are able to create a double-sided tape (DST) that is adhesive to all kinds of surfaces. Adhesion of wet surfaces is instant since the water layer on the surface is positively utilized by the DST to turn itself into a coacervate. Especially, the DST is easy to store at room temperature, which precludes the special care required in storing conditions. Besides PDDA, other biocompatible polycations, such as poly(ethylenimine) and chitosan, are all able to form coacervates with folic acid. As such, the current strategy opens up a simple, efficient, and aqueous approach to synthesize folic acid-based green

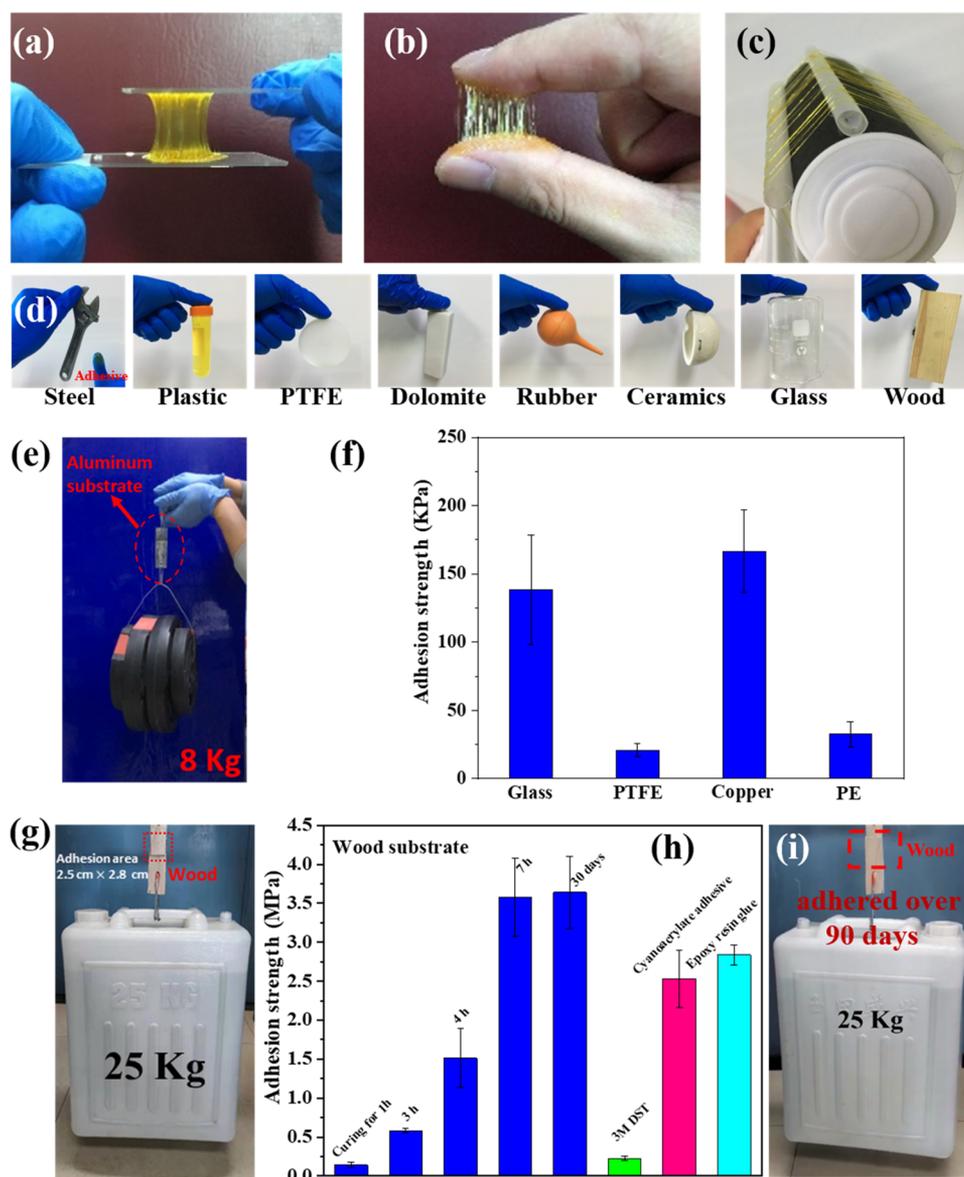


Figure 2. Adhesion property of the PF-C-9 coacervate. (a) Photographs of the PF-C-9 coacervate between two glass slices and (b) two fingers. (c) Photograph of flexible, thin, and smooth fibers mechanically pulled from the PF-C-9 coacervate. (d) PF-C-9 coacervate adhering to various surfaces. (e) Photograph of the sustained 8 kg load with adhered Al slices (PF-C-9 coacervate: 2.4 cm \times 2.4 cm). (f) Average shear adhesion strength of PF-C-9 coacervate measured for different substrates. (g) Photograph of the sustained 25 kg load with adhered wood for 12 h (PF-C-9 coacervate: 2.5 cm \times 2.8 cm). (h) Variation of the shear adhesion strength of PF-C-9 coacervate on wood with time (blue column). The other three columns show the stationary adhesion strength acquired with a commercialized 3M VHB double-sided tape, cyanoacrylate glue, and epoxy resin AB glue on wood. (i) Photograph of the sustained 25 kg load with adhered wood over 90 days.

adhesives, which is very promising in a wide range of fields ranging from industry to everyday life.

EXPERIMENTAL SECTION

Materials. Folic acid hydrate (>98.0%) was purchased from Tokyo Chemical Industry Co. Ltd., and the chemical formula was determined by element analysis as $C_{19}H_{19}N_7O_6 \cdot 2H_2O$. PDDA (35 wt % in water, $M_w < 100\,000$; 20 wt % in water, $M_w = 100\,000$ – $200\,000$; 20 wt % in water, $M_w = 200\,000$ – $350\,000$; 20 wt % in water, $M_w = 400\,000$ – $500\,000$) was obtained commercially from Aladdin and used without further purification. Sodium hydroxide (NaOH) was purchased from Xilong Chemicals with a purity above 99.0%. Cyanoacrylate (JSENB) glue was purchased from Beijing Dehang Wuzhou Technology Co., Limited. Epoxy resin AB glue (Araldite 2012) was purchased from Beijing Tiannuo Tiancheng Biotechnology Co., Ltd. All of the above chemicals were used as received. The water

used in all experiments was purified by a Milli-Q Advantage A10 ultrapure water system.

Preparation of the Wet Adhesives and Their Corresponding Freestanding Films. A folic acid (FA) solution at 0.025 mol/L with pH values ranging from 9.0 to 12.0 was prepared and adjusted with a few drops of concentrated NaOH. Then, an equal volume of PDDA solution (0.05 mol/L) was added. Turbidity was observed once the PDDA solution was added, and a fluidic wet adhesive was obtained with shaking. We named the adhesive as PF-C-X (PDDA/FA-Coacervate-X, X = 9, 10, 11, 12), indicating that the coacervate-based bulk wet adhesive was prepared by direct mixing of PDDA aqueous solution with FA salt solution (in a wide range of pH = 9–12) and applied directly. The yield of the adhesives PF-C-9, PF-C-10, PF-C-11, and PF-C-12 was calculated to be 93.7, 79.9, 82, and 81.2%, respectively.

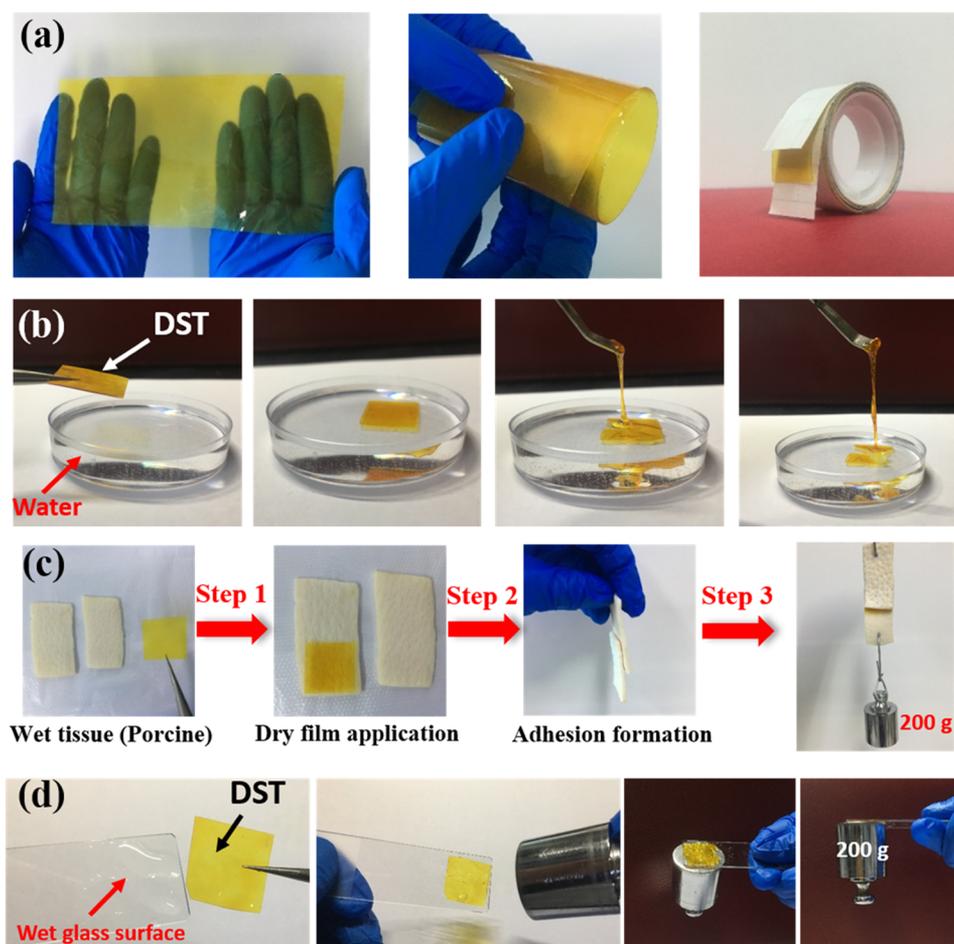


Figure 3. (a) Photograph of the freestanding flexible film and a roll of the tailored DST tape. (b) Transformation of DST into coacervate upon adding water. (c) Adhesion of fresh porcine with a 2.4 cm × 2.4 cm DST. (d) Adhesion of the wet surface of glass and a steel load of 200 g with a 2.0 cm × 2.0 cm DST.

Freestanding films were fabricated by casting a fluid-behavior PF-C-X onto a cleaned Teflon substrate, dried under air conditions for 24 h, and then peeled off from the plates, giving dry films with a thickness of around 50 μm . Here, the corresponding films were abbreviated as PF-C-X Film. Of note, much more testing and investigation have been carried out for the PF-C-9 adhesive and the corresponding PF-C-9 Film in our study, because of its highest yield, lower pH preparation, and superior comprehensive performance compared to the other three adhesives.

RESULTS AND DISCUSSION

The chemical structures of folate and PDDA are presented in Figure 1a. PDDA is a water-soluble cationic polyelectrolyte, while the solubility of folic acid (FA) in water is very poor (1.6 mg/L at 25 $^{\circ}\text{C}$) due to intramolecular hydrogen bonding,³¹ but it dissolves easily on addition of NaOH or other bases of the alkaline metal family. In this study, we used NaOH to convert FA into its sodium salt, making it soluble in water in the form of folate. Upon mixing the aqueous solution of PDDA and sodium folate of various pH values (pH = 9, 10, 11, 12) in a charge-matching stoichiometry, a highly viscous brown coacervate, termed as PF-C-X, where X = 9, 10, 11 and 12, respectively, denoting the solution pH, was formed instantly owing to electrostatic interactions between the folate anion and the PDDA polycations (Figure 1b). Excess of PDDA results in coacervation failure, and only clear solutions can be obtained, as demonstrated in the phase diagram (Figure S1).

Because no chemical synthesis procedure was involved, a large volume of PF-C-X coacervate could be prepared at the laboratory scale at once. As tabulated in Table S1, the freshly prepared PF-C-X coacervates contain a huge amount of water of 71.9, 72.4, 73.0, and 73.3% at pH 9, 10, 11, and 12, respectively. Rheological measurement suggested that all of the coacervates were viscoelastic liquids (Supporting Information, Figure S2). The viscosity of these coacervates decreased with increasing shear rates (Figure S3), indicative a dynamic shear-thinning fluid. The lyophilized coacervate under scanning electron microscopy (SEM) showed an interconnected porous three-dimensional network (Figure 1c), which was caused by the loss of water during the freeze-drying procedure. The extremely smooth surface of the network was consistent with the highly viscous and excellent flowing feature of the coacervates, so that any asperities were repaired instantly during the process of water evaporation.

Next, the adhesive ability of the PF-C-X coacervates was examined. Figure 2a shows that they could be stretched into filaments at room temperature by slowly separating two glass slides or pulling apart two fingers (Figure 2b). Flexible, thin, and smooth fibers (Figure S4, SEM image of the fibers) could be mechanically pulled from the coacervate with lengths up to several meters, illustrating its superior viscoelastic behavior. Figure 2c shows the fibers rolled up on a home-made spool. Further tests indicated that these coacervates are able to

adhere to all kinds of materials ranging from nonpolar Teflon to polar copper. Figure 2d presents the adhesion of stainless steel, plastics, poly(tetrafluoroethylene) (PTFE), dolomite, rubbers, ceramics, glasses, and wood. For a glue area of 2.4 cm × 2.4 cm, the adhered slices of Al can easily carry a weight of 8 kg (Figure 2e). To quantitatively evaluate the adhesive strength of the bulk adhesive, we performed a lap-shear measurement and applied the wet adhesive PF-C-9 to wood, copper, glass, PE, and PTFE, respectively. The freshly prepared PF-C-9 adhesive was compressed between two flat plates and the shear adhesion strength was measured 4 h later in air. As shown in Figure 2f, the strengths for the adhesion to copper, glass, PE, and PTFE were 166.6, 138.5, 32.5, and 20.9 kPa, respectively. It was noticed that the adhesion strength to wood is as high as 1.51 MPa for a contact time of 4 h, and amounts to 3.57 MPa within 7 h (Figure 2h). We assume the stronger adhesion of PF-C-9 to wood is due to the rough and water-expansive surface of wood so that it can form hydrogen bonds sufficiently with PF-C-9. Furthermore, the roughness of the wood surface may also interlock the two surfaces, thus beneficial for a strong adhesion.^{32,33} In the stable adhesion state, a weight of 25 kg can be hung up under the two adhered wood substrates with a glued area of 2.5 cm × 2.8 cm (Figure 2g), suggesting the excellent macroscopic adhesive behavior of the PF-C-9 adhesive. Notably, thermogravimetric analysis combined with online mass spectrometry (TGA-MS) measurements (Figure S5) revealed that the waterborne FA/PDDA-based adhesive releases only water vapor below 200 °C, but without formaldehyde and other toxic volatile gases. This consolidates that the FA/PDDA-based coacervate is green and safe compared to formaldehyde-based adhesives that are criticized for their toxicity issues.

It was noticed that the adhesion strength of PF-C-9 coacervate to various surfaces increases with time (Figures 2h and S6). It may take 7 h for the adhesion of two wood plates to reach the maximum adhesion strength in this study, which is mainly due to the slow evaporation of water in the coacervate pressed between two plates. Because water facilitates chain motion inside the adhesive, this is not advantageous for a firm adhesion. Only when all of the water is evaporated, which is very slow in the gap of the pressed two wood or copper plates, can firm adhesion be built due to solidification of the adhesive. Control experiments suggested that a stable adhesion strength of around 3.6 MPa can be obtained within 1 h under heating or N₂ blowing (Figure S7). Of course, the noncovalent interactions for adhesion to occur are time dependent too, where the adhesive needs to penetrate surface boundary layers, spread, and develop intimate interfacial contacts with the adherends' surfaces, and cure and set within a reasonable period.³⁴ We found that the noncovalent interaction between the substrate and the PF-C-X adhesives may attain stability within 1 h. Long-term adhesion tests confirmed that the adhesion strength did not diminish over 30 days (Figure 2h), and the adhesion strength remained and no adhesion reduction was detected in several months. As shown in Figure 2i, the adhered wood substrates are still able to hold a weight of 25 kg after storage for 90 days, thereby highlighting the long-lasting adhesive properties of PF-C-9. Strikingly, compared with industrial tapes and commercial wood glues, our wood adhesive displays the best adhesion strength no matter to wood (Figure 2h) or to copper (Table S2 and Figure S6), probably due to its better flow ability and

the hydrophilicity, so that it is able to interact sufficiently with the substrates.

The large amount of water and the excellent flow ability of the fresh coacervates allow the formation of the casting film. It was interesting to find that a freestanding transparent flexible film could be obtained after casting the coacervate onto a cleaned Teflon substrate (Figure 3a). SEM and transmission electron microscopy (TEM) measurement revealed that both the surface and the cross-section of the film are very smooth (Figure S8). No self-assembled structures were observed at both micro- and nano-scales. In line with this, the film is not birefringent (Figure S9), but is rather hydrophobic (Figure S10). The contact angle for the film obtained at pH 9 is 106.2°, indicating that the polar groups are buried in the hydrophobic ones, which should be a result of decreasing surface energy. Such a film is non-adhesive, but becomes strongly adhesive immediately upon contacting water. Figure S11 shows that the mechanical strength of the film decreases with increasing humidity. It transforms into coacervate again if sufficient water is provided (Figure 3b). This means that the coacervate can be stored in the form of a double-sided tape (DST) that can be directly applied to wet surfaces. Figure 3a shows a roll of DST made with the dried film. To test the ability of the DST in adhering wet surfaces, we measured the adhesion of two pieces of porcine in air, which is biologically similar to the human dermis. Figure 3c shows the macroscopic behavior of the DST on the freshly adhered porcine, which is able to hold a load of 200 g. Quantitative measurement was performed on the porcine, and the instant adhesion strength was recorded to be 7.1 kPa. Actually, the DST can be applied to any wet surface. Figure 3d shows the application of DST to adhere the wet surface of glass and steel. Upon dropping water onto the glass and steel surfaces, respectively, the 200 g steel load can firmly adhere to the glass with the aid of a piece of 2.0 cm × 2.0 cm dry DST. Unlike most synthetic adhesives to which water or moisture acts as a surface contaminant to prohibit adhesion, the dry DST utilizes water to form an adhesive coacervate.³⁵ In practical applications, the wet surface of the materials has to be pretreated and dried before applying commercial glue (such as 3M DST and 3M instant glue). In this regard, the DST in the current study, which is convenient and suitable for all surfaces, is very promising in practical applications. Additionally, to verify the repeatable adhesive strength of the rehydrated coacervates, all of the dry PF-C-X DST was applied on wet copper and wood substrates and the adhesion strengths were measured after curing for 24 h. As shown in Figure S12, the rehydrated coacervates could almost keep their original adhesive strength, which is ascribed to the reversible nature of supramolecular interactions. That is to say, as soon as the dry DST was mixed with water, a wet adhesive could form again with the original adhesiveness.

It should be noticed that the initial content of water used for wetting the DST would impact the adhesion performance of DST. As the water content is not enough, the contact between the adhesive and the substrate is not sufficient, which underlies the final adhesion strength. Figure S13 shows that only when the initial content of water is larger than 54.3% is the initial adhesion sufficient, and slow evaporation of water would lead to the strongest adhesion. For coacervates with much larger water content, such as the freshly prepared ones in which the water content exceeds 70%, the initial adhesion strength may not be very high, but it would amount to the strongest adhesion upon evaporation of water.

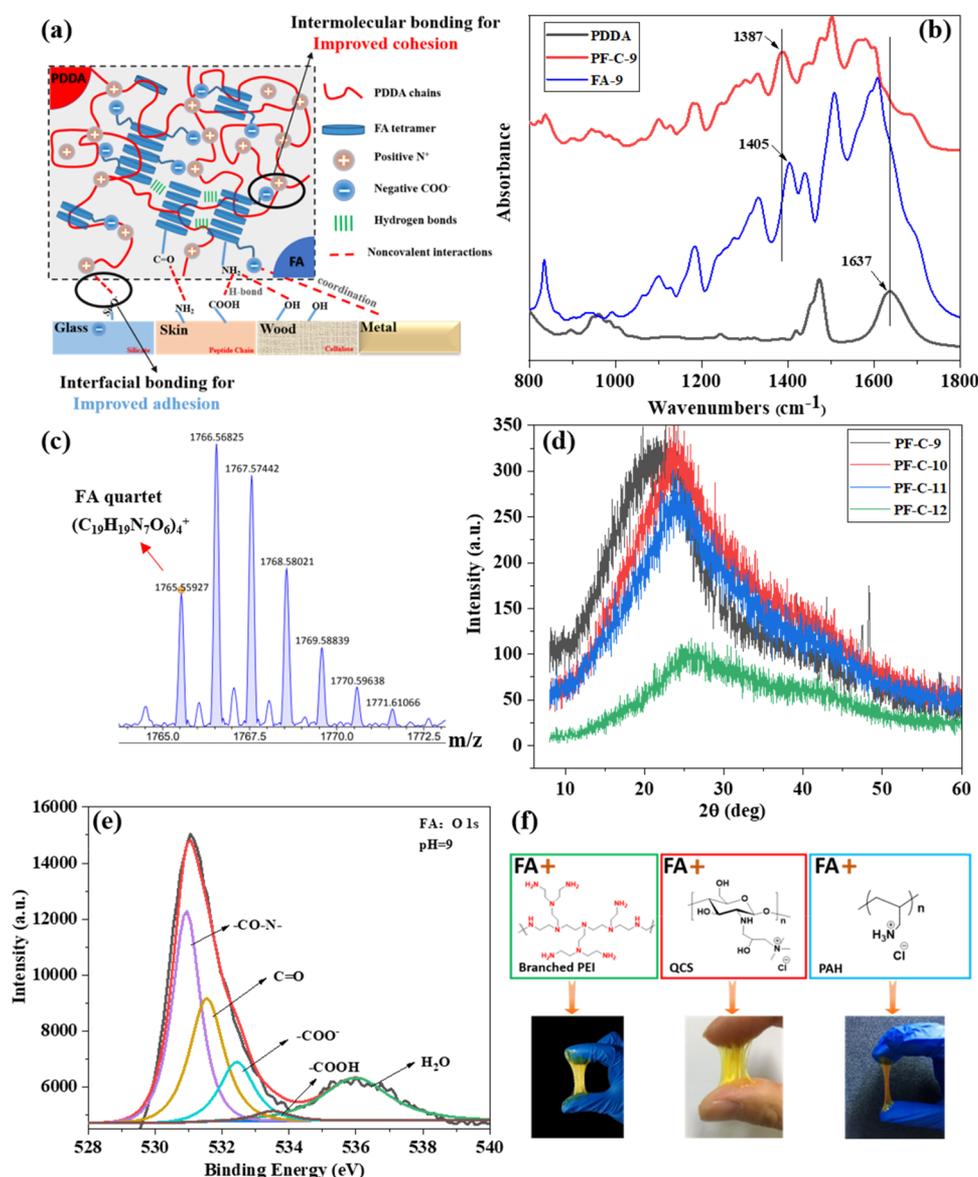


Figure 4. (a) Proposed noncovalent interactions between the adhesive FA-based coacervate and different surfaces. (b) ATR-IR spectra of folate anion (FA-9), PDDA cation, and the corresponding PF-C-9 coacervate. (c) High-resolution mass spectrometry (FT-MS) of PF-C-9. (d) XRD patterns of the PF-C-X Film in the range of 8–60°. (e) High-resolution XPS spectra (O 1s) of FA at pH = 9. (f) Generality of fabricating adhesive materials using FA and different water-soluble cationic polyelectrolytes.

The excellent adhesion ability of the folate-PDDA-based coacervate is attributed to the polyvalent internal interactions and noncovalent interactions with various surfaces (Figure 4a). As presented in Figure 4b, the symmetric vibration of the COO⁻ of folate shifts from 1405 to 1387 cm⁻¹ in the coacervate. Meanwhile, the vibration band of the N⁺-C bond at 1637 cm⁻¹ becomes less discernable. These changes suggest that electrostatic interactions have occurred between the folate anions and PDDA cations. Fourier transform mass spectrometry (FT-MS) measurements indicate that folic acid molecules have formed quartets in the coacervate (Figures 4c and S14), which is evidenced by the occurrence of a series of species with *m/z* ranging from 1765 to 1772. Because the *M_w* of folate ion is about 441, the peak with *m/z* = 1765.55927 is assigned as (C₇₆H₇₇N₂₈O₂₄)⁺, which is exactly the composition of 4 folic acids charged by 1 H⁺. The other peaks, such as *m/z* = 1766.56825, 1767.57442, 1768.58021, 1769.58839, 1770.59638, and 1771.61066, are the species of the FA

quartet containing different isotopes. XRD measurements revealed a considerable diffraction, with the spacing being 3.4–3.8 Å, indicating the FA quartets have further undergone π - π stacking (Figures 4d and S15). At pH 9, the folic acid is partially dissociated, and the ratio of folic acid to folate is close to 1:6 via X-ray photoelectron spectra (XPS) according to the area ratios between the corresponding subpeaks (Figure 4e). As a result, hydrogen bonding between carboxylates occurs to improve the cohesion property, which is further confirmed by attenuated total reflection infrared (ATR-IR) measurements (Figure S16). The ATR-IR measurements also revealed that the vibrational band of COO⁻ shifts as the coacervate contacts with copper (Figure S17), indicating that the COO⁻ group has coordinated with a metallic element. Moreover, the hydrophobic interaction and high-density H-bonds are probably the two primary factors in the adhesion of coacervate for PE and PTFE.³⁶ Furthermore, PDDA may provide positive charges in the coacervate. Although the materials are prepared in a

charge-balancing ratio, there is always excess PDDA in the coacervate. Elemental analysis reveals that the molar ratios between the DDA unit and FA at various pH values (9, 10, 11, and 12) are 2.86, 3.12, 3.19, and 3.23, respectively (Table S3). Considering each FA contains 2 carboxyl groups, the positive charge is in excess in PF-C-X coacervates of different pH values. The excess of one component in polyelectrolyte coacervate systems is very common due to the quenching of the chain conformation.^{37,38} Since most surfaces carry negative charges, the presence of excess positive charges in the adhesives is advantageous for the excellent adhesion ability.³⁹ However, strong adhesivity requires balancing of these interactions. As the solution pH increases to above 10, when all of the $-\text{COOH}$ groups are ionized (Figure S18) and the excess extent of PDDA becomes larger, the adhesion ability of the resultant coacervates decreases (Figure S19), indicating that the loss of hydrogen bonding and too much excess of positive charges are not advantageous for optimum adhesion. The strength of the network in the coacervate is critical for the excellent adhesion ability. If the ionic interaction between FA and PDDA is weakened by salt, the adhesion ability decreases (Figure S20). Similarly, the long-chained PDDA is also crucial for building a strong network, which provides the cohesion interaction in the network to strengthen the noncovalent $\pi-\pi$ stacking and ionic interaction in the coacervates. We found that only as the molecular weight of PDDA becomes larger than 100 kDa ($M_w > 100$ kDa) are the adhesive coacervates formed, and the adhesion strength increases on increasing the molecular weight of PDDA (Figure S21).

It is general that the FA-based coacervates display excellent adhesivity. We show that by replacing PDDA with other cationic polyelectrolytes, such as branched poly(ethylenimine) (bPEI), quaternized chitosan ammonium salt (QCS), and poly(allylamine hydrochloride) (PAH), similar adhesive coacervates can be obtained as well (Figure 4f). The corresponding adhesive strengths of the FA/bPEI, FA/QCS, and FA/PAH-based coacervates on glass substrate are given in Table S4. Finally, since all of these adhesives are waterborne and the cationic polyelectrolytes and FA can be easily obtained with mature synthetic chemistry, the current strategy opens up a new paradigm in developing environment-friendly adhesives through economic and facile pathways.

CONCLUSIONS

In summary, we report a facile approach to synthesize folic acid-based coacervates to fabricate excellent wet adhesives with long-lasting adhesiveness. Owing to the formation of a quartet, which further undergoes $\pi-\pi$ stacking, folic acid may behave like a polyanion to interact with a polycation to form a viscous coacervate. Hydrogen bonding and electrostatic interaction strengthen the internal cohesion inside the coacervate, whereas the excess polycations, hydrogen bonding, and coordination may work cooperatively to bind to surfaces, which makes the coacervates robust adhesives to all surfaces. The FA-based coacervates can be fabricated into DST, which is facile for storage and application. The current work opens up a new avenue for the design and development of non-catechol-based adhesives, which shows obvious advantages such as easy and green processing, low cost, and large-scale preparation. We envision that by combination with covalent bonding, a much better wet adhesive can be synthesized in the near future.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsami.1c06844>.

Water content of the freshly prepared wet adhesive PF-C-X; elemental analysis of the prepared PF-C-X films; phase diagrams of FA/PDDA mixture at pH = 9; rheological behavior of the PF-C-X wet adhesive; viscosity of the PF-C-X wet adhesives; polarized optical microscopy (POM) for the PF-C-9 film; high resolution mass spectrometry (FT-MS) of the prepared films; effect of pH on the adhesion strength of PF-C-X coacervates on copper surface (PDF)

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Notes

The authors declare no competing financial interest.

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